IDENTIFICATION OF CRITICAL SOURCE AREAS WHICH CONTRIBUTE NUTRIENTS TO SNOWMELT RUNOFF

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ABSTRACT

The presence of nutrients in snowmelt runoff from agricultural watersheds has been reported by previous studies. However, no study has answered the most important question “what areas of the watershed contribute nutrients to snowmelt runoff?” or addressed the factors that control snowmelt runoff water quality. This study was designed to (1) find the areas that contribute nutrient to snowmelt runoff (termed as critical source areas, CSA), and (2) understand the source and transport factors that control the snowmelt runoff water quality in the Canadian prairies. The findings of this study will provide vital information to understand snowmelt runoff water quality and for sustainable management of soil nutrients and snowmelt runoff water quality in the Canadian prairies.

Source and transport factors and snowmelt runoff water quality were studied for two years on shoulder, backslope and footslope landform segments. The distribution of fall soil nutrients in the top 5 cm soil layer (available soil P [ASP], nitrate [NO_3^-] and ammonium [NH_4^+]), snow depth, snow water equivalent (SWE), snowmelt runoff and snowmelt runoff water quality (total P [TP], total dissolved P [TDP], NO_3-N and sediment) were studied using closed and open plots placed on each landform segment. The influence of source and transport factors was evaluated in relation to snowmelt runoff water quality.

The ASP had a distribution pattern of backslope < shoulder < footslope in 2003 before manure application (bma) and shoulder = backslope = footslope in 2004. The NO_3^- distributed as shoulder = backslope = footslope in 2003 (bma) and shoulder < backslope < footslope in 2004. However, NH_4^+ had a stable distribution of shoulder = backslope < footslope in 2003 bma and in 2004. The pre-melt SWE increased in the down slope direction having the lowest in the shoulder and backslope and the highest in the footslope in 2005. The average daily snowmelt runoff from 1 m^2 plots did not vary between the shoulder and the backslope. Infiltration was dominant in 2004 while runoff

was dominant in 2005. Of the three landform segments, the shoulder was the greatest contributor of runoff to the depression. The backslope contributed the least.

Hog manure injection did not seem to influence snowmelt runoff water quality. Most nutrients and sediments were from the land surface. Analysis revealed that fall soil nutrient concentrations were not a dominant factor controlling the nutrients in the snowmelt runoff in this site. However, snowmelt runoff volume controlled snowmelt runoff water quality. Snowmelt runoff water quality did not vary between the landform segments. However, as a result of the dominance of shoulder in this landscape, the total transport of nutrients and sediment was the highest from shoulder. Where landform characteristics are similar to the study watershed, it may be argued that all landform segments are CSA. Runoff volume is the most influential factor in determining the importance of CSA and controlling the snowmelt runoff water quality.

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DEDICATION

This thesis is dedicated to my loving parents, K.R. Gunadasa (Father) and H.L. Maginona (Mother), and my dearest wife, Chandima Karunanayake, whom always gave me encouragement for the success in my academic career.

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LIST OF ABBREVIATIONS

$\bar{x}$	Mean
°	Degrees
°C	Centigrade
ama	After manure application
ANOVA	Analysis of Variance
ASP	Available Soil Phosphorus
B	Boron
BS	Backslope
bma	Before manure application
BMPs	Best Management Practices
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium Carbonate
$CaPO_4$	Calcium Phosphate
CSA	Critical Source Area
Cu	Copper
CV	Coefficient of Variation
DEM	Digital Elevation Model
EC	Electrical Conductivity
Fe	Iron
FS	Footslope
FW	Flow Weighted
GIS	Geographic Information System
K	Potassium
LSD	Least Significant Difference
LTN	Long Term Normal
Max.	Maximum
Mg	Magnesium
Min.	Minimum
Mn	Manganese
N	Number of samples
Ns	Not significantly different
N	Nitrogen
NH_3	Ammonia
NH_4-N	Ammonium Nitrogen
NO_3^-	Nitrate
NO_3-N	Nitrate Nitrogen
O_2	Oxygen
OM	Organic Matter
Org C	Organic Carbon
Org N	Organic Nitrogen
P	Probability value
P	Phosphorus
PI	Phosphorus Index

PO_4-P	Phosphate Phosphorus
S	Sulfur
SAR	Sodium Absorption Ratio
SH	Shoulder
SO_4^{-2}	Sulphate
SWE	Snow Water Equivalent
TC	Total Carbon
TDN	Total Dissolved Nitrogen
TDP	Total Dissolved Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
WHC	Water Holding Capacity
Zn	Zinc
A	Statistical significance level

CHAPTER 01

1.1 Introduction

Snowmelt runoff and its water quality is very important issue in Canadian prairies. Approximately 85% of the average annual runoff comes from snowmelt (Granger et al., 1984). When accumulated seasonal snow cover melts in the spring and generates runoff, it provides a precious source of water for domestic, livestock and irrigation purposes as well as for wildlife habitats such as wetlands and lakes in this region (Gray and Male, 1981). Snowmelt water recharges the soil moisture which is a precious source of water for the agricultural production in this region. It also recharges ground water resources by deep percolation (Hayashi et al., 1998).

Quality of snowmelt runoff in Canadian prairies is an important issue which has drawn much attention in recent years. Presence of nutrients such as phosphorus (P) and nitrogen (N) in snowmelt runoff from agricultural lands have been reported in few studies (Burwell et al., 1975; Ginting et al., 1998; Elliott and Maulé, 2001). The snowmelt runoff in Canadian prairies has higher potential to transport these nutrients to a greater distance than rainfall runoff does as snowmelt runoff occurs when the soil is still frozen. Therefore, these nutrients may end up in surface water bodies such as lakes and wetlands in this region and trigger the eutrophication in these surface water bodies

(Gaynor and Findlay, 1995; Richardson and King, 1995). However, research focused on the quality of snowmelt runoff from agricultural lands in the Canadian prairies is very limited and this is especially true for snowmelt runoff from agricultural lands with hog manure application. The water quality of snowmelt runoff from agricultural lands with hog manure application is of growing importance since the application of hog manure to agricultural lands in the region is increasing (Pastle et al., 1999) and many producers in western Canada prefer to apply manure in the fall rather than in the spring to (a) spread their work load, and (b) reduce spring tillage operation.

Livestock industries, especially the hog industry, make considerable contribution to the agricultural economy of Canadian prairies (Julian, 1999). These industries produce a large amount of manure, which has received a lot of attention in recent years both as a source of fertilizer and as a source of pollution. Therefore, manure should be managed carefully so that there are no harmful effects to the environment. Land application of manure to recycle nutrients through the soil-plant system has been a commonly accepted method of disposal (Sultton et al., 1978). Manure application provides numerous advantages to the farmers, such as (a) minimizing the cost for the conventional (inorganic) fertilizers thereby reducing the cost of production; (b) improving soil physical and chemical conditions favorable for agricultural production (Campbell, 1978; Sweeten and Mathers, 1985; Xie and MacKenzie, 1986; Burns et al., 1987; Sommerfeldt et al., 1988; Chase et al., 1991; Dormer, 1997; Qian and Schoenau 2000; Buckley et al., 2001); and (c) increasing crop yield (Choudhary et al., 1996; Anderson, 2002). Despite these advantages, the application of manure onto agricultural lands has raised the concern about the impact on surface water quality. The effect of land-applied manure on the quality of rainfall-generated runoff waters has been studied extensively (Edwards and Daniel, 1993; Sharpley et al., 1994; Catt et al., 1998; Hansen et al., 2001; Gburek et al., 2002; Enright and Madramootoo, 2004). However, there is limited information on the water quality of snowmelt runoff from agricultural lands where hog manure has been applied in the fall.

There are many factors controlling nutrient losses from manure-applied agricultural lands to surface waters through runoff (Tisdale et al., 1993; Daniel et al., 1994; Sharpley et al., 1994; Sutton, 1994; Chang and Entz, 1996). These factors can be sorted into two major groups; the transport factors (for example; runoff) and the source factors (for example; nutrients from manure and/or fertilizer and from soil). Therefore, movement of nutrients from agricultural land to surface waters depends on the coincidence of source and transport factors. In the most simple sense, the interaction of surface runoff source areas with nutrient source areas (where fertilizer and/or manure has been applied producing excess nutrients available for transport), results in critical source areas (CSA) that control nutrient export (Gburek et al., 1996). These CSA are most vulnerable to nutrient losses in runoff and are identifiable areas within a catchment. The CSA concept is a relatively new concept and during the past decade some studies have delineated CSA (Sharpley, 1995; Gburek et al., 2000; Eghball and Gilley, 2001) in relation to the phosphorus transport in rainfall runoff. However, the CSA concept has not been applied to snowmelt runoff situations and to study the quality of snowmelt runoff. Further, factors that control the nutrient loss in snowmelt runoff have not been fully understood.

Based on the CSA concept, it is clear that both transport and source factors together are required before there is a surface water quality problem. Therefore, we hypothesize that snowmelt runoff quality is also controlled by the combination of both source and transport factors. Understanding source and transport factors in relation to snowmelt runoff quality will offer useful information to develop site specific management strategies to preserve the quality of surface waters. Nutrient and water quality management efforts can be targeted to the CSA to improve their effectiveness.

The presence of nutrients and sediments in snowmelt runoff from agricultural watersheds has been reported by previous studies (Ginting et al., 1998; Elliott and Maulé, 2001). However, no study has addressed the most important fundamental question "what areas of the watershed contribute nutrients to snowmelt runoff?" This question should be addressed before anything else so that nutrient and water quality management efforts can be targeted to the areas which contribute nutrients to snowmelt runoff to improve their effectiveness. Therefore, this PhD research was designed to find the answer to this very important question for snowmelt runoff conditions in the Canadian prairies.

The main objective of this research study is to identify the areas (CSA) which contribute nutrients to snowmelt runoff and to apply the CSA concept to understand the factors that control the quality of snowmelt runoff from agricultural land which receives fall-application of hog manure. To achieve the main objective of the thesis, source (soil residual nutrients with or without hog manure injection and snow cover nutrients) and transport (snowmelt runoff) factors in relation to snowmelt runoff water quality are studied on selected landform segments, shoulder (SH), backslope (BS) and footslope (FS), and their importance is evaluated in relation to nutrient transport in snowmelt runoff from agricultural lands. Transport and source factors in relation to snowmelt runoff water quality in Canadian prairies have not been fully understood.

Landform segments (i.e. SH, BS and FS) of the watershed are used in this study to identify the CSA (i.e. areas that contribute nutrients to snowmelt runoff) to ensure (a) the reproducibility of the land areas tested for source and transport factors of the snowmelt runoff water quality and (b) the easy identification of CSA by the farmers. The landform segmentation procedure developed by Pennock and Corre (2001) was used in this study. The landform segmentation procedure provides a quantitative definition for the SH, the BS and the FS based on a combination of slope gradient and curvature (Pennock and Corre, 2001). Pennock and Corre (2001) reported that these landform segments have ideally distinct ranges of both soil taxa and rates of soil processes. They further reported that landform segments are functionally unique areas that can be used as the basis to compare across the landscapes and to implement imposed treatment or manipulative design. The other advantage of having landform segments is that farmers do not need expertise to recognize landform segments (upper, middle and lower slope segments) and their approximate areal extent.

Although the main objective of this research is addressed in total by chapters 2 to 6, and the line of research running through these chapters is coherent, these chapters (except chapter 6) have been written as stand-alone research papers. Each paper addresses specific research objectives and has an appropriate literature review to set the context for the work and to interpret the results within the paper. Each paper also contains a complete methods and materials section. Thus there will be a degree of redundancy of information, which is inevitable when using this format.

Chapter 2 provides important background information on hog manure (a possible nutrient source to snowmelt runoff in this study), factors influencing nutrient losses through runoff and CSA concept. The objectives of **Chapter 2** are to review literature on (1) hog manure, its composition, application, and its influence upon soil properties and crop yield; (2) factors influencing P and N losses through runoff (both snowmelt runoff and rainfall runoff); and (3) the CSA concept and methods developed to delineate CSA.

The distribution of soil residual nutrients in the landscape in the fall should be an important factor that would determine the quality of snowmelt runoff. The nutrient distribution observed at the beginning of the spring or during the growing season will not necessarily be the same as the distribution in the fall because of active processes during the growing season in the prairies such as soil erosion, nutrient addition to the soil through fertilizer and manure, nutrient uptake by crops and nutrient losses from the soil due to various processes. Therefore, a study of the distribution of soil residual nutrients in the landscape in the fall before soil freeze-up is important. Investigation of how soil nutrients (a source factor) are distributed in the landscape in the fall is a prerequisite to (a) study snowmelt runoff water quality; (b) identify possible CSA which could contribute nutrients to surface water resources through snowmelt runoff; and (c) rank the importance of CSA. However, previous studies have not focused on the soil nutrient distribution in the fall before soil freeze-up and soil nutrient distribution in the soil-runoff interactive layer (i.e. top 5 cm of soil). Therefore, the primary objectives of **Chapter 3** are: (1) to investigate the distribution of fall soil nutrients (soil P and N) of the top 5 cm of soil in the landscape before soil freeze-up; and (2) to study how hog manure injection in the fall affects the soil nutrient distribution in the soil-runoff interactive layer. Hog manure injection below the soil-runoff interactive layer is considered as one of the best manure application methods, as it minimizes the nutrient losses through runoff and volatilization.

The knowledge of spatial variability in snowcover characteristics (i.e. snow depth, snow density and snow water equivalent [SWE]) and snowmelt runoff across the landscape is vital information to study snowmelt runoff water quality. Further, contribution of snowmelt runoff from each landform segment to the central depression should be estimated to identify the CSA. This knowledge in conjunction with soil residual nutrient distribution in the fall will be useful to identify CSA and to understand the factors that control the snowmelt runoff water quality. However, snowmelt runoff generation at different landform segments and the relative contribution of landform segments to the water balance of a depression have not been studied in Canadian prairies. Therefore, the main objectives of **Chapter 4** are: (1) to investigate the spatial association between snow cover characteristics (snow depth, snow density and SWE and topography; (2) to investigate the spatial association of snowmelt runoff generation with landform segments using open and closed runoff plots; and (3) to estimate the snowmelt runoff contribution from different landform segments on water balance of the depression at the end of snowmelt runoff period.

The quality of snowmelt runoff, from agricultural land where hog manure had been injected in the fall, is addressed in **Chapter 5**. The objectives of chapter 5 are: (1) to investigate the quality of snowmelt runoff (total phosphorus [TP], total dissolved phosphorus [TDP], nitrate-nitrogen [NO_3-N] and sediment) from agricultural land where hog manure had been injected; (2) to investigate the spatial association between quality of snowmelt runoff and landform segments; and (3) to understand the importance of snowmelt runoff (transport factor) and fall soil residual nutrients (source factor) on snowmelt runoff water quality. Greater understanding of factors that control the snowmelt runoff water quality in the Canadian prairies and the presentation of snowmelt runoff water quality for different landform segments with injected hog manure in the fall will be the significant contributions of this chapter to the existing knowledge gaps.

Chapter 6 synthesizes the findings of chapters 3, 4 and 5 and tests the validity of the CSA concept in snowmelt conditions. In this chapter, areas that contribute nutrients to snowmelt runoff (CSA) are identified and ranked based on their importance. A conceptual model for nutrients and sediment loads in snowmelt runoff from different landform segments in an agricultural landscape is also presented.

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CHAPTER 02

Literature Review

2.1 Abstract

Movement of nutrients from agricultural non-point sources to surface waters depends on the coincidence of source and transport factors. Good understanding of source and transport factors provides useful information for the development of site specific management strategies to protect the quality of surface waters. Therefore, the objectives of this chapter are: (1) to review literature on one of the source factors; hog manure application, its composition and its influence on soil properties and on crop yield; (2) to review the literature on the critical source area (CSA) concept, and on methods developed to delineate CSA.

Manure application to the soil supplies nutrients that can be directly used by plants. However, nutrient availability from the manure depends on several factors including moisture content, feed composition, climatic conditions, bedding materials, manure storage, types and age of hogs, and manure handling methods. Manure application also influences soil biological, chemical and physical properties to varying degrees. Manure application accelerates biological activity that ultimately makes nutrients available to plants. Manure also contains high concentrations of salts which can create soil salinization, high sodium absorption ratio (SAR), with regular manure application. Further manure application influences the soil properties such as soil structure, aggregation, density, water holding capacity (WHC), infiltration and aeration to varying degrees. Nutrient loss from manure applied field depends on a number of processes including adsorption, precipitation, mineralization, plant uptake, solute transport, runoff and erosion.

There have been few studies on delineation of CSA, since the CSA concept is comparatively new. The original phosphorus index (PI) and its modified versions have been commonly used to delineate CSA. The PI has been mostly tested under natural or simulated rainfall conditions in humid environments. Systems based on geographic information systems (GIS) have also been used to identify the CSAs. The PI has never been applied to identify CSAs for snowmelt runoff conditions.

Key words: Manure, Critical Source Area, Nitrogen, Phosphorus.

2.2 Introduction

Manure is a valuable and renewable resource that can be used effectively for soil improvement and crop production. Numerous studies have shown the benefits of manure application to the soil and to the crop production (Campbell, 1978; Sweeten and Mathers, 1985; Campbell et al., 1986; Xie and MacKenzie, 1986; Burns et al., 1987; Sommerfeldt et al., 1988; Chase et al., 1991; Choudhary et al., 1996; Dormer, 1997; Qian and Schoenau 2000; Buckley et al., 2001; Anderson, 2002; Assefa et al., 2004). However, runoff from the agricultural lands receiving manure could result in increased nutrients concentrations of phosphorus (P), and nitrogen (N) in surface waters (Edwards and Daniel, 1993; Sharpley et al., 1994; Catt et al., 1998; Pote et al., 2001; Gburek et al., 2002; Enright and Madramootoo, 2004). Contribution of nutrients through runoff to surface waters may further accelerate during spring snowmelt in Canadian prairies due to the fact that frozen soil allows less infiltration than non-frozen bare soils. However, nutrients in snowmelt runoff and its related factors have not been studied in detail by most studies.

Nutrient losses to the surface waters from the manure-applied fields is governed by many factors (Tisdale et al., 1993; Daniel et al., 1994; Sharpley et al., 1994; Sutton, 1994; Chang and Entz, 1996; Grant et al., 2004). All these factors can be sorted into two major groups; the transport factors (for example; runoff) and the source factors (for example; nutrients from manure and/or fertilizer and from soil). Therefore, movement of nutrients from an agricultural land to a surface water body depends on the combination of nutrient source and transport factors (Gburek et al., 1996). The interaction of areas where runoff is generated within a watershed, with areas of excess nutrients available for transport, delineates the CSA that control nutrient export (Gburek et al., 1996). These CSA are most vulnerable to nutrient losses in runoff and are specific identifiable areas within a catchment.

Good understanding of source and transport factors that control nutrient transport to the surface water bodies will provide useful information for the development of site specific management strategies to protect the quality of surface waters (Sharpley, 1995) and sustainable manure application. Therefore, one of objectives of this chapter is to review literature on manure as a possible nutrient source in this study and to understand manure effects on soil chemical and physical properties as well as crop production. In addition, modes and forms of nutrient (especially P and N) loss from manure applied fields are briefly reviewed in this chapter. Emphasis will be placed on hog manure and its field application as our research is focused on quality of snowmelt runoff from a field that has had hog manure applied as a fertilizer. The understanding on hog manure composition, its influence on soil physical and chemical properties is of growing importance since the application of hog manure to agricultural lands in Canadian prairies is increasing.

Based on the CSA concept, it is clear that either transport factors or source factors alone cannot cause the surface water quality problem. Therefore, efforts to manage soil nutrients and to protect water quality must be targeted to the CSA where source and transport factors are met. Resource managers must recognize land areas with critical non-point source pollution problems and make priorities to target available capital resources toward implementation of conservation programs and best management practices (BMP). Understanding on CSA concept and methods available to delineate CSA will be very useful for sustainable management of soil nutrients and water quality. Therefore, another objective of this chapter is to review the literature on the CSA concept and methods developed to delineate CSA.

2.3 Literature Review

2.3.1 Composition of manure

Hog manure can provide most plant nutrients and can reduce or replace the need for commercial fertilizer to supply nutrients. However, the nutrient composition of manure (Table 2.1) could vary considerably depending on factors such as moisture content, feed composition, climatic conditions, bedding materials, manure storage, types and age of hogs, and manure handling methods (McDonald, 2000; Saskatchewan Soil Conservation Association, 2000).

Climatic conditions during manure storage influence mineralization which determines the nutrient composition of manure. Microbial activity is stimulated by warm temperatures and thus microbial decomposition of manure is increased, provided there is sufficient moisture in the manure (Arrington and Pachek, 1980). However, microbial decomposition of manure will be lower in very cold or dry climatic conditions as microbial activity is reduced under these conditions (Arrington and Pachek, 1980). Manure handling and storage methods will also have an effect on manure N as N is particularly susceptible to losses through volatilization as ammonia (NH_3) or denitrification of nitrate (NO_3^-) (Bennett and Olsen, 1996).

For freshly excreted hog manure, Barrington and Moreno (1995) reported 10.5 % dry matter content and a total N (TN) concentration of between 4000 and 9000 mg L^{-1}. Charles (1999) reported that the major portion of N in liquid hog manure is in the plant available form. The inorganic form of N in manure is mainly found as ammonium-nitrogen (NH_4-N) (Charles, 1999; Malley et al., 2002). Malley et al. (2002) also reported that 94% of total dissolved N (TDN) of hog manure was in NH_4-N. Malley et al. (2002) further reported that TDN contributed 45-98% to the TN of hog manure.

Nutrients in organic forms are not readily available for plant use and must undergo a mineralization process to be transformed into inorganic forms which are plant available. The N content, the carbon (C): N ratio of the manure and soil characteristics such as soil pH, moisture and temperature, all influence the rate of organic N (Org N) mineralization from manure (Beauchamp, 1983; Schepers and Mosier, 1991).

Table 2.1 Summary of nutrient analysis from liquid hog manure samples (Adapted from Charles, 1999).

	TN	NH_3	Org N	P	K	Dry Matter (%)
Average (g L^{-1})	21.2	14.2	6.2	15.2	12.0	2.8
Minimum (g L^{-1})	1.7	0.7	0.3	0.4	0.3	0.1
Maximum (g L^{-1})	57.5	42.9	35.4	98.1	37.0	12.5

Manure P is present in both organic and inorganic forms. Inorganic phosphate (i.e. orthophosphate form) is the plant available form of P. In liquid hog manure, P is mainly found in the solid fraction (Saskatchewan Soil Conservation Association, 2000). In general, inorganic forms of P accounts for 45% to 70% of manure P (hog and cattle) and organic P (Org P) makes up the rest of total P (TP) (Zhang et al., 2002). Malley et al. (2002) reported that TDP was the dominant part of TP of hog manure. The Org P is mineralized by soil microorganisms into inorganic P. The P mineralization rate is influenced by factors such as temperature, soil moisture, and soil pH (Zhang et al., 2002). Zhang et al. (2002) further reported that the availability of manure P varies from 80% to 100% as compared to 100% P availability in commercial fertilizers.

2.3.2 Influence of manure application on soil chemical properties

The influence of manure on soil chemical and physical properties is governed by manure application rate, time and method. Further, various factors such as climatic conditions, soil properties, crop types and nutrient mineralization rate can have an influence upon management decisions that affect the rate, time and method of manure application. Choudhary et al. (1996) reported that maximum nutrient benefit from hog manure can be obtained when manure is incorporated immediately after surface application to minimize the nutrient losses.

Mathers and Stewart (1970) found that cattle feedlot manure supplied enough N for corn or sorghum without excess NO_3^- in the soil profile when applied up to 22 Mg ha^{-1}. Vitosh et al. (1973) reported that manure continues to release available N beyond the year of application. When animal manure was applied to the soil in excessive rates (100 Mg ha^{-1} or more of hog and cattle manure), NH_3 accumulated in the soil, temporarily slowing the formation of NO_3^- (Smith and Peterson, 1982). Dormer (1997) observed that available N was increased when liquid hog manure was applied at a rate of 200 kg N ha^{-1} to a Solonetzic soil in southern Saskatchewan.

Land application of manure could increase the organic matter (OM) and TN in the soil (Sommerfeldt et al., 1988). An increase in available P following land applications of manure was reported by Chang et al. (1991) and Eghball and Power, (1995). Manure is usually applied at application rates based on N without consideration given to the amount of P in the manure. Excess P is supplied when manure is applied to meet the N needs of the crops, because most manure will have an average N:P ratio of 3:1 whereas major grain crops use N and P to a ratio of about 8:1 (Daniel et al., 1994). Qian and Schoenau (2000) reported that a single application of liquid hog manure had little influence on labile P (readily available portion of TP) because P was precipitated as calcium phosphate ($CaPO_4$) or was reorganized as Org P in the soil.

Increased concentrations of exchangeable K in soil with increasing application rates of manure were observed by Vitosh et al. (1973). Manure is also a source of organic sulfur (S) (Dubetz et al., 1975). Tabatabai and Chae (1991) reported that because of high C:S ratios, manure is not a good source of mineralizable S. The S in manure can also be lost due to volatilization and leaching. Castellano and Dick (1988) reported that in manure applied silty soil, the sulphate (SO_4^{-2}) level in the 0-22 cm depth was about 7 kg S ha^{-1} higher than that of the control soil, and they attributed this increase to the higher rates of S mineralization in the soils with manure amendments. Eriksen (1997) reported that concentrations of total S in pig and cattle slurry typically varied between 0.15 and 0.7 kg S m^{-3} of slurry and most of this variation was attributed to the variations in dry matter content of both cattle and pig slurry.

Increase in calcium (Ca) and magnesium (Mg) concentrations in the soil following manure application have also been reported by a number of researchers (Vitosh et al., 1973; Mathers and Stewart, 1980; Chang et al., 1991). McCalla (1974) reported that manure applications to croplands corrected Zinc (Zn) deficiencies. An increase in Zn following land application of cattle feedlot manure was reported by Chang et al. (1991). Manure also contains micro-nutrients such as Boron (B), Manganese (Mn), Iron (Fe) and Copper (Cu) (Charles, 1999). Micro-nutrients in manures are important to crop growth.

Excessive manure application can develop salt accumulations in the soil which can negatively influence crop growth and soil structure. When electrical conductivity (EC) of the soil reaches 2 dS m^{-1}, injury to salt sensitive crops can be expected (McCalla, 1974). Assefa (2002) reported a non significant but linear trend of increased EC of Black Chernozemic soils at one site with hog and cattle manure application and significantly increased EC at another site in Saskatchewan, Canada.

Repeated manure application may lead to soil acidification (Hoyt and Rice, 1977; Ukrainetz et al., 1996). Hoyt and Rice (1977) reported that applied manure could moderate acidification by buffering the soil against any decrease in pH. Ndayegamiye and Cote (1989) reported that with long term hog and cattle manure application, soil pH was not significantly affected because the soil had been limed prior to the manure treatment. Chang et al. (1990) observed a soil pH reduction due to manure application, and suggested that some soils could become acidic with continuous annual manure application. Charles (1999) reported that one time hog and cattle manure application in a Black Chernozemic soil in central Saskatchewan, Canada did not change the soil pH and soluble salt concentrations. Assefa (2002) also reported that the pH of the same soil remained unchanged after receiving four annual applications of hog and cattle manure.

Assefa et al. (2004) reported that the effect of hog and cattle manure application on soil chemical and physical properties after four annual applications at two field sites in Saskatchewan were relatively small and variable. They suggested that several years of continual manure application may be required to produce a change in soil properties that would significantly influence the soil productivity.

2.3.3 Influence of manure application on soil microbial properties

Ndayegamiye and Cote (1989) observed increased microbial activity after hog and cattle manure application into the soil. They found that populations of soil micro flora (i.e. bacteria, fungi, actinomycetes, ammonifiers and nitrifiers) were increased by manure application. Ndayegamiye and Cote (1989) reported that solid cattle manure had a greater effect on the microbial activity in the soil than liquid hog manure.

An increase in soil OM following manure applications has been observed (Hoyt and Rice, 1977; Campbell et al., 1986; Sommerfeldt et al., 1988). Organic C is a source of food for soil microorganisms and therefore, manure additions to the soil have a positive effect on microbial activity in the soil (Loro et al., 1997).

Hansen and Goyal (2001) reported that manure application initially increased pathogen (microorganisms that causes diseases and are introduced to the soil with manure application) levels in the soil but had a negligible effect on fatality of the pathogens. Hansen and Goyal (2001) could not observe rate-related persistence and reported a fairly weak positive relationship overall between manure application rate and pathogen populations in the soil.

Freital et al. (2003) observed higher microbial activity in soils that received cattle manure than in soils that received hog manure or urea during a field experiment with canola, spring wheat, and barley crops between 1997 and 2000 near Humboldt, Saskatchewan. They reported the presence of potential human pathogens such as *Rahnella*, *Serratia*, *Proteus*, *Leclercia*, and *Salmonella* species in soils that received cattle manure and presence of *Pseudomonads* as the dominant species in the hog manure treated soil. They further reported that fecal coliform populations were increased with increased hog manure rates. Application of urea, hog manure, or cattle manure to the soil did not increase foliar disease in wheat, barley, and canola (Freital et al., 2003).

2.3.4. Influence of manure application on soil physical properties

Manure addition to the soil increases soil porosity and reduces bulk density, when manure is applied over a long period of time (Campbell, 1978; Sweeten and Mathers, 1985). After long term applications of various types of manure, Hafez (1974) observed an increase in water stable aggregates and a reduction in bulk density of the soil in manured plots compared to unmanured plots. Mathers and Stewart (1980) also observed an increase in soil OM with a simultaneous decrease in bulk density in manured soil. Rose (1991) reported that long-term application of manure decreased soil bulk density.

Manure applications also enhance soil aggregation. Paul and Clark (1996) reported that manure additions could indirectly promote the formation of soil aggregates by stimulating microbial activity in the soil. Soil microorganisms play a significant role in soil aggregation by binding soil particles together (Paul and Clark, 1996).

Hoyt and Rice (1977) reported that manure application to the soil increased the WHC of the soil. Sowiak (2003) also reported increased WHC in soil due to hog manure application.

The increases in WHC are a function of both manure type and quantity added to the soil (Hafez, 1974). The increased WHC reported by Hillel (1980) was attributed to the increase in soil OM due to extended manure application. Organic matter improves the WHC and structure of soil (Hillel, 1980).

Manure application enhances the soil tilth. Fogg (1978) reported that the improvement in the tilth from manure application depends on the soil conditions at the time of manure application. The degree of improvement in the tilth with manure application was greater in less productive soils (Fogg, 1978). Sommerfeldt and Chang (1985) reported that manure application enhanced soil tilth as indicated by a strong inverse correlation between draft of tillage equipment and manure application rate. Campbell et al. (1986) reported similar findings and they observed that the manure-applied soil was more friable and less compacted than soils receiving inorganic fertilizer.

Mazyrak et al. (1955) reported an increase in infiltration rate after manure application. Mathers et al. (1977) reported increased infiltration rates in a clay loam soil after three annual applications of farmyard manure. However, Weil and Kroontje (1979) reported reduced infiltration rates in a clay loam soil with manure application.

Hafez (1974) reported that manure application reduces surface crusting. This could facilitate seedling emergence. The OM additions with manure could also increase soil temperature by darkening the soil and thus positively influencing microbial activity in the soil. However, after eleven annual applications of feedlot cattle manure, Sommerfeldt and Chang (1985) found that although the manure darkened the soil there was no accompanying increase in soil temperature, but, rather the manure had a cooling effect.

McCalla (1974) reported that salt accumulations in the soil caused by excessive applications of manure can damage soil structure. Soil structure is damaged when too much sodium accumulates and the damage can be observed in increased soil compaction and reduced infiltration (McCalla, 1974).

2.3.5 Influence of manure application on crop yield

A number of studies have been carried out to study the influence of manure application on crop yield. Sutton et al. (1978) reported increases in corn yield with increasing rate of liquid hog manure application (surface application) on a silt loam soil. Hultgreen et al. (2001) reported that the injection of hog manure into forages increased seed and forage yield regardless of the application rate. The hog manure application rate of 74,000 L ha^{-1} applied every second year showed excellent yield increases over the control plots in years following manure application (Hultgreen et al., 2001). A study in east-central Saskatchewan (Anderson, 2002) showed that hog manure used as a source of fertilizer in an annual cropping system was an economically sound practice in the east-central region. Thoma et al. (2005) found no difference in corn yield between manure and commercial fertilizer treatments when averaged over three years of study.

A number of studies reported that hog manure application resulted in higher or similar crop yields than inorganic fertilizer (Xie and MacKenzie, 1986; Burns et al., 1987; Chase et al., 1991, Buckley et al., 2001). However, Miller and Mackenzie (1978) reported lower corn yield in the first year of manure application compared with inorganic fertilizer. Choudhary et al. (1996) reported increased crop yield with increasing rate of hog manure application, but observed that yield variation depended on the actual application rate, the method of application, the type of soil and growing conditions (Choudhary et al., 1996). Buckley et al. (2001) reported that increasing rates of hog manure improved the head density and yield of oat and barley varieties in low fertility soil.

Hog manure has also been shown to improve crop quality by increasing plant nutrient concentration not only in the year of hog manure application but also in subsequent years (Choudhary et al., 1996). Alberta Agriculture, Food and Rural Development (2005) reported that swine manure injection could correct growth limiting factors such as P, K and S in alfalfa.

2.3.6 Factors affecting pollutant losses from manure applied fields

Nutrient losses through runoff and erosion are affected by climate, topography, and agronomic factors (Sharpley et al., 1996). Adsorption, precipitation, mineralization, plant uptake, solute transport, runoff and erosion are the key processes by which nutrient losses are controlled (Grant et al., 2004).

2.3.6.1 Phosphorus losses

Usually manure is applied to the soil to meet the N demands of the crops and this can cause an excessive P application to the soil. Therefore, P accumulates in the top soil layer with manure application and can be lost to surface waters in dissolved and particulate forms through runoff (McDonald, 2000).

When considering the potential of soil to release P and pollute surface waters, the soil's ability to absorb (or fix) and release P is an important factor to be considered (Cogger and Duxbury, 1984). Phosphorus is relatively immobile in calcareous soils (Tisdale et al., 1993). Phosphorus losses via leaching are limited in soils with high base saturation as P binds with Ca to form Ca-P precipitates (Tisdale et al., 1993). McDonald (2000) reported that aluminum and iron oxide content in acidic soils is the most important factor controlling P fixation. Aluminum and iron fix soil P and remove it from the soil solution thus minimizing the P losses with runoff (McDonald, 2000). Further, factors such as soluble Ca, calcium carbonate ($CaCO_3$) in alkaline soils, OM, pH and soil texture also influence soil P fixation (McDonald, 2000). Grant et al. (2004) reported that repeated manure application to the soil reduced the adsorption and precipitation of P by soil due to the adsorption sites being occupied. Grant et al. (2004) further reported that due to manure contribution to P stocks at the soil surface, the concentration of P in sediment transported in runoff also increased.

Romkens and Nelson (1974) and Sharpley et al. (1994) reported that manure addition to soils where P concentrations are elevated can cause an environmental risk. Significant P losses have been observed through runoff from manure applied fields, particularly on sloping landscapes (Daniel et al., 1994). Pote et al. (1996) reported that the concentration of P in runoff is positively correlated to the concentration of P at the soil surface.

With up to 30 years of experimental data on N and P export in runoff from a typical agricultural watershed within the Chesapeake Basin in Pennsylvania, Pionke et al. (2000) reported that most of the P export with the surface runoff occurred from the areas near the stream. Pionke et al. (2000) further reported that about 90% of the algal-available P exported in runoff was generated during the largest seven storms per year. However, Pionke et al. (2000) reported that most of the exported NO_3^- originated as subsurface flow entering the soil or ground water some distance from the stream and most of the NO_3^- transport occurred during non-storm flow periods.

Mueller et al. (1984a, 1984b) showed that runoff, erosion, and TP losses were reduced when surface applied solid dairy manure was incorporated (chisel plow). Edwards and Daniel (1993) showed that the TP and soluble P concentrations in runoff were linearly related to the rate of hog manure application to the surface of fescue plots. However, both the loading of contaminants and the concentration of contaminants in runoff must be considered for water quality impacts. Unlike P concentration in runoff, the P load cannot be predicted based on [only] the P concentration in the soil (Edwards and Daniel, 1993). Ginting et al. (1998) showed that the net loss of TP in runoff from a corn field after solid beef manure application was less than for a corn field with no manure addition. Thus, the influence of manure addition on the net loss of P in runoff depends on the combined effects of the manure on runoff and on P availability in the soil.

2.3.6.2 Nitrogen losses

Sutton (1994) reported that liquid manure injection was the best method of manure application in terms of minimizing N losses via volatilization. Volatilization as NH_3 is the major cause of N loss from a manure applied field (Manitoba Agriculture Food and Rural Initiatives, 2001). Nitrogen loss through volatilization is greatest for unincorporated manure. Manure injection into the soil or incorporation soon after application can greatly reduce the N loss through volatilization (Manitoba Agriculture Food and Rural Initiatives, 2001). A number of factors such as soil pH, temperature, soil moisture, $CaCO_3$, wind velocity and depth of manure incorporation control the N volatilization (Manitoba Agriculture Food and Rural Initiatives, 2001).

Large N losses can also occur through denitrification following application of manure to the soil (Loro et al., 1997, Manitoba Agriculture Food and Rural Initiatives, 2001). Following manure application, increased consumption of oxygen (O_2) by microbes and limited diffusion of O_2 together create the anaerobic conditions necessary for denitrification (Loro et al., 1997). Carbon from the manure stimulates microbial respiration and water, from the liquid manure and rainfall, limits O_2 diffusion in the soil. Factors such as soil OM, limited O_2, neutral or alkaline soil pH, and soil temperature are favorable to the denitrification (Manitoba Agriculture Food and Rural Initiatives, 2001).

The N applied to soil, as animal manure can also be lost through leaching and this is particularly significant in coarse textured soils. Organic-N and NH_4-N in manure are converted to NO_3^- which is available for plant uptake and mobile in soil. Therefore, N applied through manure can be leached into ground water. Mathers and Stewart (1974) reported that cattle feedlot manure application rates should be less than 22 Mg ha^{-1} to minimize N losses via leaching. However, the inorganic N in manure may not be available for crops because of N immobilization (Paul and Beauchamp, 1994). Available N applied through manure should not exceed crop requirements (Chang and Entz, 1996).

2.3.7 Research on critical source areas

There are many factors controlling the nutrient losses through surface runoff to the surface waters from manure-applied agricultural lands (Tisdale et al., 1993; Daniel et al., 1994; Sharpley et al., 1994; Sutton, 1994; Chang and Entz, 1996). These factors can be sorted into two major groups; the transport factors (for example; runoff) and the source factors (for example; nutrients from manure and/or fertilizer and from soil). Therefore, movement of nutrients from an agricultural land to surface waters depends on the coincidence of source and transport factors. Within a watershed CSA can be found in areas where transport factors coincide with a source factor to transport nutrient to surface waters (Beegle et al., 2005).

A phosphorus index (PI) was developed by Lemunyon and Gilbert (1993) as a simple tool to identify CSA by considering the relative importance of source and transport factors which control P losses in runoff. The PI index is commonly used to rank P loss vulnerability of individual sites. Sharpley (1995) evaluated the PI upon a number of watersheds where erosion and TP losses were monitored and found a good relationship between the PI value and the TP loss. Gburek et al. (1996) demonstrated that application of the PI to unit source areas (i.e. small units of land with single land use and management) has the capability to identify P loss vulnerability when one site is compared against another site. Modification to the original PI was introduced by Gburek et al. (2000) to account for lack of runoff potential for some areas and to account the proximity to and potential for contributing to the streams through surface runoff.

With rainfall simulation experiments to evaluate the relative importance of the variables included in the PI, Eghball and Gilley (2001) showed that soil erosion accounted for 78% and 88% of the TP and particulate P losses respectively for the cropland conditions in Nebraska. This indicates the importance of erosion in the loss of sediment bound P. Eghball and Gilley (2001) further reported that the bio-available and dissolved P losses were not related to soil erosion but were affected by tillage practices, runoff amount and P source. Based on the results of this study, Eghball and Gilley (2001) modified the weighting factors of the PI and showed high correlation ($R^2 = 0.74$) between TP loss and the modified PI value.

Using readily available data on transport and sources of P, Birr and Mulla (2001) used the modified version of the PI for 60 watersheds located within Minnesota to rank P loss vulnerability at a regional scale. Birr and Mulla (2001) modified the PI for a regionally based analysis of the PI with the following modifications to the original PI; (a) the proportion of cropland and pastureland within 91.4 m of drainage channels and streams was also included as a transport factor; and (b) weighting factors for organic P application rate and soil test P level were reduced from 1.0 to 0.5 and weighting factor for fertilizer application rate was increased from 0.75 to 1.0. Birr and Mulla (2001) validated this modified PI using long term water quality data and concluded that, with certain limitations, the modified PI could be used at the regional scale to rank P loss vulnerability.

In a pilot project in Quebec, Simard et al. (2000) modified the original PI by adding components including the degree of P saturation in soil to describe the risk of P contamination of surface waters by P. The indicator was estimated at the Soil Landscapes of Canada polygon scale (1:1,000,000). This study reported that a large proportion of the intensive agricultural areas, particularly those of with concentrated livestock production have a high risk of P contamination through runoff (Simard et al., 2000). The original PI and modified versions of it have been applied to identify areas vulnerable to P loss through rainfall runoff in studies throughout the USA. However, this index has not been tested for snowmelt runoff conditions to recognize CSAs that are vulnerable to nutrient losses through snowmelt runoff. Further, a literature search revealed that no method has been developed to identify areas which contribute nutrients to surface waters through snowmelt runoff.

The PI is the most commonly used method to rank the watersheds based on their risk of P loss to runoff. However, methods like GIS and mapping techniques have also been used to delineate potential CSA. Tim et al. (1992) used an integrated approach coupling water quality computer simulation modeling with a geographic information system (GIS) to define CSA at the watershed level. They combined two simplified pollutant export models with the GIS to estimate soil erosion, sediment yield, and P loading from the Nomini Creek watershed located in Westmoreland County, Virginia.

2.4 Summary

Manure application supplies plant available macro-nutrients such as N, P, K and micro-nutrients (e.g. Cu and Zn) into soil. Manure nutrients that are not in the plant available form are mostly in the manure OM. Microbial activity converts nutrients in manure OM to plant available forms. However, nutrient composition of manure could vary considerably depending on numerous factors such as moisture content, feed composition, climatic conditions, bedding materials, manure storage method, handling method, and type and age of animal.

Manure also contains high levels of salts which can cause high SAR and EC in the soil, and could cause soil salinization in the long term with regular application of manure. Manure application can also influence soil pH to varying degrees depending on several factors such as manure and soil characteristics, application rate, and number of manure applications. Manure additions to the soil have a positive effect on soil microbial activity. The increased microbial activity due to manure application and OM content can improve soil structure by helping to bind soil particles into aggregates. Soil properties such as soil structure, aggregation, density, WHC, infiltration and aeration are affected to varying degrees by manure application. Manure application results in increased crop yield depending on actual manure application rate, the method of application, the type of soil and growing conditions.

Manure application based on N demands of the crops can cause P accumulation in the top soil layer. This accumulated P can be lost to surface waters in dissolved and particulate forms through runoff. The P losses through runoff from soil, receiving manure, depend on numerous factors such as absorption and release of P by the soil, aluminum and iron oxide content, acidity and alkalinity, soluble Ca, OM, pH, soil texture, the number of manure applications, manure application method and time, and topography. The N applied to soil through manure can be lost in surface runoff but these losses are less significant agronomically than losses due to leaching (particularly significant in coarse textured soil), volatilization, denitrification, and immobilization of applied N.

The CSA concept is a comparatively new concept and there have been very few studies to demonstrate the delineation of CSA. Many of these studies have used the PI and its modified version in the delineation of CSA and most tests have been under natural or simulated rainfall conditions in humid environments. GIS based systems have also been used to identify the CSAs. However, these analytical tools cannot be directly applied to snowmelt runoff conditions, as they were not originally developed for snowmelt runoff conditions and are not readily available or practical for everyday use by resource managers.

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CHAPTER 03

Impact of slope position and hog manure injection on soil P and N distribution in an undulating landscape in Saskatchewan, Canada.

3.1 Abstract

A study on distribution soil nutrients of the soil-runoff interactive layer over the landscape in the late fall is a prerequisite to identify critical source areas (CSA), and to understand the factors that control the snowmelt runoff water quality. Therefore, the objectives of this study are to investigate (1) the distribution of soil residual nutrients in the landscape before soil freezing and (2) how manure injection in the fall affects the nutrient distribution.

The study site, located in an undulating landscape on the Canadian prairies, is a closed drainage basin with moderate to fine textured soils, and received injected hog manure in the falls of 2001 and 2003. The landscape was classified into the shoulder (SH), backslope (BS) and footslope (FS) landform segments using a digital elevation model (DEM). Soil samples, collected from each landform segment in the falls of 2003 and 2004, were analyzed for available soil phosphorus (ASP), nitrate (NO_3^-) and ammonium (NH_4^+) and soil moisture.

In the undulating landscape, the distribution pattern of ASP was not stable (e.g. backslope < shoulder < footslope in 2003 before manure application [bma] and shoulder = backslope = footslope in 2004). The distribution of NO_3^- was also unstable in the top 5 cm soil layer (e.g. shoulder = backslope = footslope in 2003 bma and shoulder < backslope < footslope in 2004). However, NH_4^+ concentrations had a stable distribution pattern (e.g. shoulder = backslope < footslope in 2003 bma and in 2004). Hog manure injection increased NO_3^- and NH_4^+ immediately after manure injection. However, one year after manure application, the manure effect could only be seen with the ASP. Soil NO_3^- and NH_4^+ concentration were stable for each landform segments irrespective of the manure injection (e.g. concentration in 2003 bma = concentration in 2004 for footslope, backslope, and shoulder).

Key Words: Fall soil nutrients, Landscape position, Hog manure, Critical source areas.

3.2 Introduction

Based on the CSA concept (Gburek and Sharpley, 1998), contributions of phosphorus (P) and nitrogen (N) from a agricultural watershed to surface water bodies through snowmelt runoff should be primarily controlled by the interaction of P and N source factors (such as fall soil P and N and nutrients released from crop residues and snow cover) with transport factors (snowmelt runoff). Therefore, prevention of nutrient losses with snowmelt runoff from agricultural lands should target the areas that combine excessive soil P and N levels in the fall with high snowmelt runoff potential. In order to implement control measures that reduce or prevent the nutrients from contributing to the surface waters with snowmelt runoff, the spatial variability of soil nutrients (i.e. P and N) across the landscape in the fall should be known.

Investigation of how soil P and N are distributed in the landscape (spatial variability) in the fall will provide vital information for understanding the interaction of soil nutrients with snowmelt runoff and help to identify CSA that contribute nutrients to the surface water resources through snowmelt runoff. Assessment of spatial variability of soil nutrients is also important in making land use decisions, implementation of variable rate fertilizer application, identification of mapping units, design of field experiments and scaling of field studies to regional scales (Soil Survey Staff, 1975; Pennock et al., 1987; van Kessel et al., 1993; Fiez et al., 1995, Stevenson et al., 1995).

Numerous studies have investigated the distribution of soil nutrients in the landscape (Pennock et al., 1987; Halvorson and Doll, 1991; Parkin, 1993; Hairston and Grigal, 1994; Pennock et al., 1994). Most studies reported soil nutrient and moisture distribution measured in soil depths greater than 5 cm at the beginning of the growing season (e.g. spring) or during the growing season. However, the spatial distribution of fall residual soil nutrients in the top 5 cm layer is the most important factor that would determine the quality of snowmelt runoff. The nutrient distribution observed at the beginning of the spring or during the growing season will not necessarily be the one we can expect in the fall because of the active processes such as soil erosion, nutrient addition to the soil, nutrient loss from soil due to different processes (e.g. leaching, volatilization, immobilization) or nutrient uptake by crops during the growing season in the prairies. To properly delineate CSA for spring snowmelt it is essential to consider the fall spatial distribution of soil nutrients in the landscape. Therefore, a study which focuses on the fall spatial distribution of soil nutrients in the landscape before soil freeze up is important to understand and to manage the quality of snowmelt runoff water. Here, we assume that nutrient distribution patterns in the landscape in the late fall immediately prior to soil freezing will reflect the nutrient distribution pattern at the time of snowmelt runoff generation.

The primary objectives of this study are; (1) to investigate the spatial distribution of residual soil nutrients (soil P and N) in the runoff-soil interactive layer in the fall across the landscape before soil freeze-up and; (2) to study how fall hog manure injection affects the amount and distribution of soil nutrients in the runoff-soil interactive layer. This study focused only on ASP and N, which are crucial nutrients in terms of crop production and surface water quality.

3.3 Literature Review

Topography contributes an important role in agricultural lands by shaping the soil's spatial variability, surface and subsurface hydrology, and crop yields. Across the landscape, the spatial variability of soil and soil properties can be assessed using different methods. For example, spatial soil nutrient variability can be evaluated by sampling soils within soil map units (Carr et al., 1991), by sampling soils at intensive grids laid out in the landscape (Wibawa et al., 1993) or by sampling soils from slope positions quantitatively classified using a DEM (Pennock et al., 1987). Using the DEM, Pennock et al. (1994) identified and classified slope positions into four groups of landform segments; SH, BS, FS and level based on their position in the landscape and morphological characteristics. The summit and the depression areas are included in the level segment.

Surface topography, water redistribution and soil type are the major factors controlling soil variability at the landscape scale (Parkin, 1993). Topography modifies both the microclimate and hydrological conditions within a landscape (Rowe, 1984). Zaslavsky and Sinai (1981) reported that the water flow pathways are controlled by the slope gradient and slope form. Thus, heterogeneous water distribution across the landscape could occur due to the differences in topography and soil across the landscape. In a hummocky landscape, water is redistributed to convergent areas such as the FS and lower slope segments (Zaslavsky and Sinia, 1981; Pennock et al., 1987).

Most of the agricultural lands in the Canadian prairies are characterized by hummocky or undulating landscape (Pennock et al., 1987). In this landscape, water redistribution is the primary control of nutrient cycle, soil productivity, and crop yield (Pennock et al., 1987). Halvorson and Doll (1991) reported that the greatest soil water and nutrient content are in lower slope positions (e.g., FS) and lower slope positions generally produce the highest crop yield (Halvorson and Doll, 1991). Several studies (Pennock et al., 1987; Halvorson and Doll, 1991; Hairston and Grigal, 1994; Pennock et al., 1994) have demonstrated that water redistribution patterns in the landscape explain the majority of variability in soil properties and strong relationships exist between slope position and soil properties and profile characteristics. Redistribution of water, solute and solids from upper slope (SH) to lower slope (FS) positions due to gravity is associated with variable topography (Hairston and Grigal, 1994; Pennock et al., 1994). Thus, Pennock et al. (1987) reported that higher soil moisture contents could be expected in convergent landscape elements than in divergent elements and generally soil moisture varies in the sequence of SH < BS < FS. Increase in soil water in the down slope direction has been frequently documented (Ruhe, 1975; Schimel et al., 1985; Butler et al., 1986, Stevenson et al., 1995). Stevenson et al. (1995) found 32% higher soil moisture contents at the FS relative to the SH in the thick Black Soil Zone near Birch Hills, Saskatchewan.

The above spatial relationship between landscape position and soil moisture is not always evident. For example, coarse-textured soils with high infiltration eliminated the landscape effect on soil moisture (Helvey et al., 1972). Miller et al. (1988) observed that a spatial pattern of soil moisture could be absent under conditions where fine-textured soil exists and below normal precipitation occurs.

Crop nutrient uptake (eg. N and P) across the landscape is largely a function of differences in water availability, and the level of nutrients which vary in the landscape. Therefore, much of the variability in crop yield in the semi-arid regions can be explained by topographic differences (Rennie and Clayton, 1960; Malo and Worcester, 1975). Gregorich and Anderson (1985) observed that higher moisture levels, higher infiltration and subsequently greater vegetative growth, along with the redistribution of soil to lower slope positions resulted in increasing organic C (Org C), available N and P content from the SH to the FS. Similar findings were reported by Anderson (1985) for an eroded hilly area in the Brown Soil Zone of Saskatchewan. Fiez et al. (1994) and Halvorson and Doll (1991) also reported increasing organic matter (OM) content and available NO_3^- from upper to lower slope positions. Qian and Schoenau (1995) reported higher NO_3^- release from FS soils of higher OM compared to SH soils.

Variation of plant available N at different landscape positions is mainly controlled mainly by the spatial variation in net N mineralization (Qian and Schoenau, 1995; Jowkin and Schoenau, 1998). Net mineralization is influenced by OM content, the readily mineralizable N content of OM, texture, water content, soil structure, temperature, pH, and the carbon (C)/N ratio of added OM. Many of these properties

(OM content, texture and water content) vary across the landscape (Afyuni et al., 1993; Goovaerts and Chiang, 1993; Brubaker et al., 1994; Hook and Burke, 2000). Plant available N also varies with management practices such as tillage and crop type especially with leguminous crops. Although the response of N mineralization to different management practices has been considered by numerous researchers, little of this work has been done on variable landscape. Dharmakeerthi et al. (2005) reported that most of the landscape variation in plant available N within a season was associated with the variation of organic matter in the landscape. They further reported that the spatial pattern of plant available N was temporally stable, and suggested that factors affecting plant available N could have temporal consistency in the spatial patterns.

Most research on nutrient availability in the landscape has not considered P. Solohub et al. (1996) observed a significant landscape effect on the pre seeding bicarbonate extractable P in Black Chernozemic Soils at Birch Hills, Saskatchewan, Canada. The P levels in the lower levels and depressional positions were the highest followed by the FS; the SH contained the least sodium bicarbonate extractable P (Solohub et al., 1996). Cahn et al. (1994) observed that NO_3^- and phosphate P (PO_4-P) data collected across the landscape were highly skewed due to several outlying values and suggested that high values could represent sites of high microbial activity or localized accumulation of nutrients.

Most of the above studies focused on the soil nutrient and moisture distribution in the spring or during the growing season. However, distribution of soil nutrients in the landscape in the late fall, immediately prior to soil freezing, is the most important factor that would determine the quality of snowmelt runoff in Canadian prairies. The nutrient concentrations and distribution observed in the spring (after snowmelt and soil is thawed) or during the growing season will not necessarily be the same as the distribution in the fall because of active processes during the growing season in the prairies such as soil erosion, nutrient addition to the soil and losses from soil and nutrient uptake by crops. Therefore, a study on soil residual nutrients and its distribution in the landscape in the late fall before soil freeze-up is very important.

3.4 Site Characteristics

The experimental site was a small drainage basin (average slope is 2.7%) of 8249 m^2 chosen within one farm field as being representative of the local landscape. The site is located near the town of Elstow (52º 02’ N, 106° 06’ W), 55 km east of the city of Saskatoon, Saskatchewan, Canada. The site is identified as a closed drainage basin, where snowmelt runoff generated within the watershed during the spring accumulates in the central depression (Figure 3.1) until it completely infiltrates over several weeks. The area has an undulating landscape with local small hilltops and depressions consisting of fine textured lacustrine material over till. The soil is classified as an Orthic Dark Brown Chernozem of the Elstow Association (Acton and Ellis, 1978) consisting of medium to moderately fine textured, moderately calcareous, clayey glacio-lacustrine deposits (ADF, 2002). Soil texture of the upper 15 cm of soil is clay loam to silty clay.

A meteorological station, installed at the site, recorded temperature and rainfall data from 2002 to summer 2005. For comparison purposes, climatic normals (1971-2000) from the town of Viscount (51° 57' N, 105° 37' W) about 30 km to the east of the site, were used (Environment Canada, 2005). The mean annual air temperature at Viscount is 2.5°C, with a monthly mean of -16.8 °C in January and 18.1 °C in July (1971-2000). Monthly air temperatures are generally below 0 °C from November through March. Therefore, a hydrological year for the province where the research site is located is defined starting on 01 November and ending on 31 October (Hayashi et al., 1998). A hydrological year consists of a winter (November to March), a spring (April and May), a summer (June to August) and a fall (September and October). The mean annual precipitation at Viscount is 412 mm, of which 84 mm occurs in the winter, mostly as snow, 184 mm during the three summer months of June, July and August and 63 mm during the fall (1971-2000 climate normal).

The field, within which the study watershed is located, received agitated hog manure at the rate of 56.2 m^3 ha^{-1} (approximately 125 kg N ha^{-1} and 36 kg P ha^{-1}) in fall 2001 and fall 2003. Hog manure was supplied by a near-by (about 2 km south east of the site) hog barn operated through the Prairie Swine Centre and the application rate was based on the common hog manure application rate in the province. Manure application in the fall 2003 was done on 2 October 2003. Manure was applied in east to west direction by a commercial operator. Knife openers injected the manure to a depth of 10-12 cm and a compaction wheel followed to close the injection slots. Reduced tillage practices are used on this field. With the exception of manure application, the seeding operation was the only tillage in the reduced tillage system in use at the study site. An air seeder with sweep openers was used to seed and the soil was subsequently harrowed and packed. The site has been under crop production (mainly cereal grains such as wheat and oil seeds such as canola) for the length of the cropping record (20 years). In 2003, canary seed (*Phalaris canariensis*) was grown in the site while wheat (*Triticum aestivum* L.) was grown in 2004. Crops had been harvested at the time of manure application and soil sampling and the average stubble height was about 15 cm. According to visual observations, the stubble density was higher in the FS than the BS or the SH in both years.

This chapter presents the results of soil nutrient (P and N) analysis of soil samples collected in the falls of 2003 and 2004. The study period was characterized by a relatively dry summer and fall in 2003 (143 mm and 45 mm respectively) and a normal summer (183 mm) in 2004 followed by a dry fall (32 mm) (Figure 3.2). Summer and fall in 2003 were warmer (17.4 °C and 7.8 °C respectively) than normal temperatures, whereas summer and fall 2004 were cooler (14.2 °C and 6.4 °C respectively) than normal (Figure 3.2).

3.5 Materials and Methods

3.5.1 Topographic analysis and landform segmentation

The site was surveyed using a laser theodolite. The topographic survey taken at approximately 10 m spacing, was used to interpolate a DEM for the site. A kriging interpolator was used for developing an elevation map. The morphological attributes (i.e. aspect, plan curvature, profile curvature and gradient) for each cell of the DEM, were calculated using the programs of Martz and de Jong (1988). The terrain attributes (Table 3.1) were then used to group each cell into a discrete landform element class using pre-defined ranges of morphological and positional terrain attributes (Pennock, 2003). The landscape was then divided into landform segments (Figure 3.3) which were studied for soil nutrient distribution in the fall (2003 and 2004). Only the SH, BS and the FS were studied in this study.

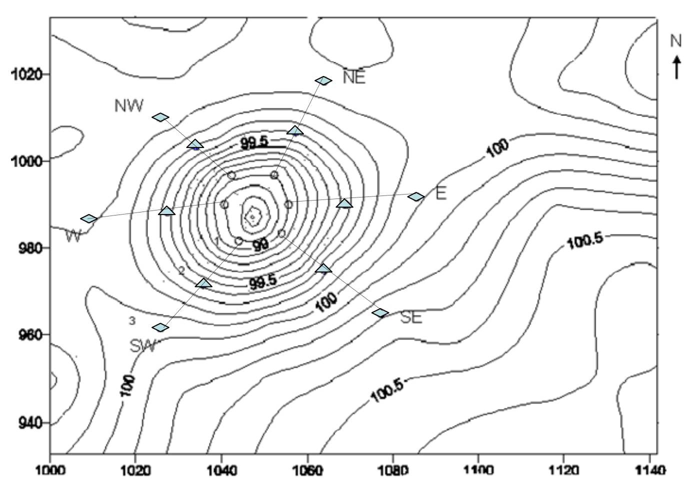

Figure 3.1 Experimental watershed with the locations of sampling points (circles refer to sample points at the FS, triangles for the BS and squares for the SH; dotted lines show the transects. Values in x and y axis are in m).

Table 3.1 Description of terrain attributes (Adapted from Pennock, 2003).

Attribute	**Description**
Elevation	Elevation above sea level or a local datum (m)
Gradient	Slope between the land surface and a horizontal plane at a given point (m m^{-1}, degree or percent)
Aspect	The compass direction that the slope segment is facing (degree)
Profile Curvature	Down-slope curvature of a slope segment; by convention, convex curvatures are assigned positive values and concave curvatures negative values (degree m^{-1})
Plan Curvature	Across-slope or contour curvature of the slope segment, by convention, convex curvatures are assigned positive values and concave curvatures negative values (degree m^{-1})

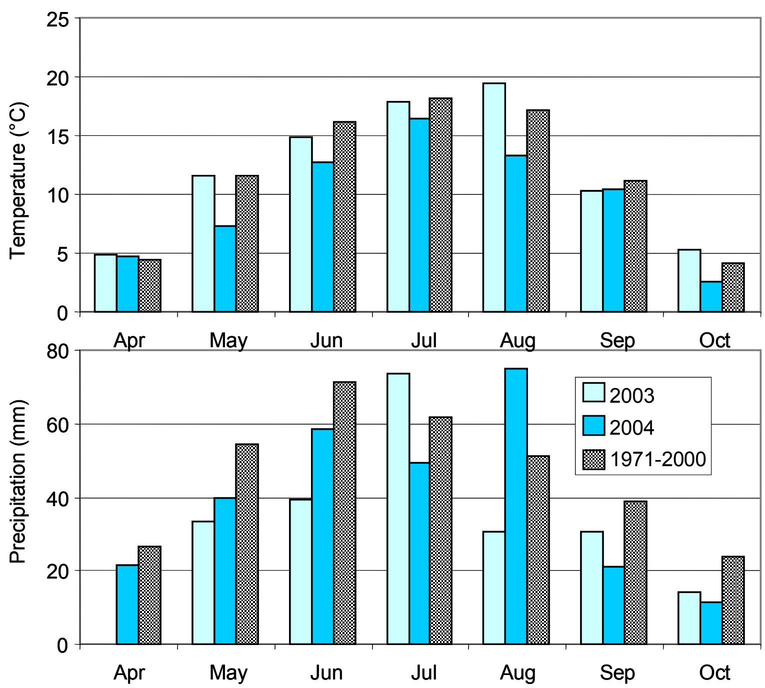

Figure 3.2 Precipitation and temperature for the study site (2003 and 2004) and long term averages for Viscount (Environment Canada, 2005).

3.5.2 Sampling

Six sampling transects were established, radiating outwards from the depression (Figure 3.1) and each running from the FS to the SH in the directions of: NE, E, SE, SW, W, and NW. Three sample locations per transect were picked such that each landform segment was represented. Soil samples were collected on 2 October 2003, before manure application (bma), and on 18 October 2003 after fall manure application (ama), and on 14 October 2004. Manure was not applied in fall 2004. At each sample location, four soil samples were taken randomly within a 2 m^2 area. Sampling errors were minimized through careful soil sample collection. Each soil sample was collected from a 33 cm (long - across injection direction) × 10 cm (wide) and 5 cm (deep) soil section using a shovel as the primary cutting tool. The dimensions of the soil sample were chosen to ensure representative inclusion of manure injection slots and inter-row areas. The samples were bulked with the three other samples from the same sample location for soil nutrient and soil moisture analysis. The depth of soil sampled (0-5 cm) represents an average effective depth of surface soil-runoff interaction for a range of soils, rainfall intensities, slopes and soil management characteristics (Sharpley, 1995). Representative hog manure samples were collected at the time of application and were analyzed for manure N and P (Table 3.2). Nearly 61 % of the N in the hog manure was in the available form (mostly as NH_4^+) while 20 % of total phosphorus (TP) was in the available form. Daniel et al. (1994) and Schoenau et al. (2000) also reported similar results with liquid hog manure.

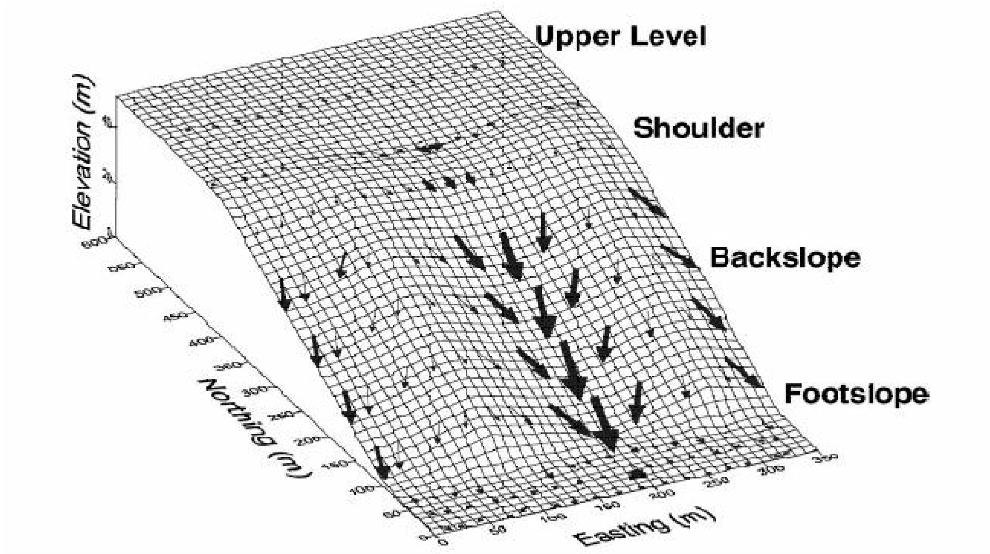

Figure 3.3 Schematic diagram of relative locations of landform segments with surface water flow on the surface. The size of arrows indicates the depth of water flow at that point on the surface (Adapted from Pennock, 2003).

Table 3.2 Nutrient analysis from liquid hog manure samples in fall 2003

Manure Samples	TN & TP (H_2SO_4 Digested)		Available N & P[#]	
	TN (mg N kg^{-1})	TP (mg P kg^{-1})	NH_4^+ (mg kg^{-1})	P (mg kg^{-1})
Sample 1	2255	648	1656	106
Sample 2	2207	648	1858	152
Mean	2231	648	1757	129

[#] modified Kelowna extraction method for P and 2M KCl extraction for N

3.5.3 Laboratory analysis

All soil samples were air dried and sieved (to less than 2 mm) before analyzing for ASP using the modified Kelowna extraction (Qian et al., 1994) and for soil NO_3^- and NH_4^+ using 2M KCl extraction (Keeney and Nelson, 1982). Soil samples collected in fall 2004 were also analyzed for TN, TP, Org C and Total C (TC) but 2003 samples were not analyzed for these parameters because of the budgetary constraints. The TN, and TP were determined by sulfuric acid-peroxide digestion at 360 °C (Thomas et al., 1967), followed by colorimetric determination of N as NH_4^+ and P as orthophosphate using Technicon TM automated colorimetry. The Org C and TC were determined using a LECO Carbonator TM automated combustion C analyzer using the method of Wang and Anderson (1998). Inorganic C was calculated by subtracting Org C from TC. Soil moisture contents were determined in fresh soil samples collected in fall 2003 and fall 2004 before processing, by oven drying (105 °C for 24 hours). The TN and TP of the hog manure samples were analyzed by sulfuric acid-peroxide digestion at 360 °C (Thomas et al., 1967), followed by colorimetric determination of N as NH_4^+ and P as orthophosphate using Technicon TM automated colorimetry. The available P in hog manure samples was determined using modified Kelowna extraction (Qian et al., 1994) and NH_4^+ in the manure samples was determined using 2M KCl extraction (Keeney and Nelson, 1982).

3.5.4 Data analysis

The ASP, NH_4^+, NO_3^- and soil moisture values for each landform segment were initially grouped into box plots, which allow both the median and dispersion of values to be visually assessed. The results were tested for normal distribution with Shapiro-Wilk statistics using the *Proc Univariate* function of SAS (SAS Institute, 1999). As the data from each landform segment approximated a normal distribution, parametric statistics were used to compare ASP, NH_4^+, NO_3^- and soil moisture values between landform segments. The results were evaluated using a one-way Analysis of Variance (ANOVA) and a least significant difference (LSD) multiple comparison to assess the significance of the difference between pairs of landform segments (results of the ANOVA are reported in Appendix I). The significance level (α) was set at 0.05.

3.6 Results and Discussion

3.6.1 Soil characteristics

Means of TN, TP, TC and Org C of the surface 5 cm layer of soil collected in fall 2004 increased from the SH to the FS (Table 3.3). Previous studies (Honeycutt et al., 1990; Pennock and Corre, 2001; Landi et al., 2004) reported that the Org C increases from the SH to the FS and related this trend to long term transport of fine OM and lateral movement of clay from higher elevations. The Org C may also be related to the biomass productivity which is affected by moisture redistribution in the landscape. The Org C of the surface 5 cm layer in this undulating landscape increased from the SH to the FS. However, the Org C at only the FS was only significantly different from other landform segments. There was no significant difference observed between the BS and the SH in terms of Org C. The lack of significant difference between the SH and the BS indicated that these two segments were homogeneous with respect to Org C. Therefore, the Org C concentration did not show the sequence of SH < BS < FS as observed in the previous studies (Honeycutt et al., 1990; Pennock and Corre, 2001; Landi et al., 2004) and instead it showed the sequence of SH = BS < FS. Concentrations of inorganic C (less than 1% of soil mass) were relatively low and were not significantly different between slope segments. Therefore, the distribution of TC was largely influenced by the Org C and thus these two carbon measurements had a similar distribution pattern of SH = BS < FS.

Although the mean TP increased from the SH to the FS (Table 3.3) it was not significantly different between the SH and the BS. However, the TP at the FS was significantly different from other landform segments. Therefore, TP of the 5 cm soil layer had the distribution pattern of SH = BS < FS in this undulating landscape.

The TN increased in the downslope direction and the TN was significantly different between the landform segments. Therefore, TN of the 5 cm soil layer had the distribution pattern of SH < BS < FS in this undulating landscape. The inorganic portion of TN, expressed as sum of NO_3^- and NH_4^+ concentrations, was 92, 44 and 23 mg kg^{-1} of soil respectively for the FS, BS and the SH. Variation of plant available N has been recorded between different landform segments (Jowkin and Schoenau, 1998), and this variation has been attributed to spatial variation in net N mineralization (Qian and Schoenau, 1995). Net mineralization is influenced by OM content and the readily mineralizable N content of OM, texture, water content, soil structure, temperature, pH, and the C/N ratio of OM. Many of these properties (OM content, texture and water content) are known to vary across sloping landscapes (Afyuni et al., 1993; Goovaerts and Chiang, 1993; Brubaker et al., 1994; Hook and Burke, 2000).

Table 3.3 The TN, TP, TC and Org C of the surface 5 cm soil layer in fall 2004 at the landform segments (mean value of six samples for each landform segment)[##].

Soil Parameters [#]	FS	BS	SH	F/P value[¶]
TN (mg kg^{-1})	2836^{a} (5%)	2057^{b} (10%)	1607^{c} (17%)	$55.2/1.2\times10^{-7}$
TP (mg kg^{-1})	1001^{a} (4%)	759^{b} (8%)	743^{b} (5%)	$59.4/7.4\times10^{-8}$
TC (%)	5.5^{a} (9%)	4.0^{b} (9%)	3.7^{b} (6%)	$38.0/1.3\times10^{-6}$
Org C (%)	4.6^{a} (7%)	3.4^{b} (8%)	3.0^{b} (14%)	$36.5/1.7\times10^{-6}$

[##] *CV values are reported in parenthesis.* [#] *Means with same letters are not significantly different at α = 0.05. Lower case letters are used for mean comparison between columns (between landform segments).*
[¶] *From ANOVA table. F, F statistics from ANOVA table; P, probability value of F statistics from ANOVA.*

3.6.2 Fall soil moisture content

In fall 2003, soil moisture at the SH, BS and the FS were not significantly different from each other (Table 3.4). In fall 2004, soil moisture in the same layer of soil at the FS was significantly different from the BS and the SH (Table 3.4), while the SH and the BS were homogeneous again in terms of soil moisture. The semi arid climate of this region results in the potential evapotranspiration usually exceeding the growing season's precipitation and thus most available soil moisture is used by the crop. Therefore, in the fall, pronounced variability in soil moisture with landform segments may not be expected. Furthermore, the 5 cm layer of the soil is also exposed to drying through evaporation.

Table 3.4 Soil moisture contents for different landform segments in fall 2003 and in fall 2004 (mean value of six samples for each landform segment) ##.

	#Soil Moisture (%)			
	FS	BS	SH	F/P Value¶
Fall 2003	22^a (5%)	22^a (10%)	20^a (8%)	$3.9/4.0\times10^{-2}$
Fall 2004	26^a (12%)	21^b (7%)	18^b (10%)	$19.9/5.9\times10^{-5}$

CV values are reported in parenthesis.# Means with same letters are not significantly different at α = 0.05. Lower case letters are used for mean comparison between columns (between landform segments).
¶ From ANOVA table. F, F statistics from ANOVA table; P, probability value for F statistics from ANOVA table.

In fall 2004, the FS was significantly wetter than the BS and the SH and this could be due to fact that August was considerably wetter than normal (Figure 3.2) and growing season precipitation throughout the year was sufficient to sustain the crop. As a result, moisture reserves at the FS were not exhausted by the crop. In fall 2003, the above condition was not observed and this could be due to dry summer conditions in 2003. Miller et al. (1988) also indicated that the spatial distribution pattern of soil moisture was absent when below normal precipitation occurred. The other landform segments (the SH and the BS) were not different in terms of fall soil moisture levels in both years and this could be due to the gentle slope (less than 2.7%) across which these segments would, therefore, not have a strong influence on soil moisture redistribution, soil texture, infiltration or water holding capacity (WHC) (Helvey et al., 1972; Miller et al., 1988) in this landscape which would lead to a homogeneous moisture distribution between the SH and the BS.

3.6.3 Available soil phosphorus

3.6.3.1 Variation of available soil phosphorus between falls

The mean ASP concentration for each landform segment showed an increase (Table 3.5) between fall 2003 bma and fall 2004. It is possible that some of this increase was due to the hog manure injection. The mean ASP concentration of each landform segment after manure application in fall 2003 was not significantly different from the concentration observed before manure application in fall 2003. This could be attributed to: (1) the shallow soil sampling depth of 0-5 cm while the manure injection was done to the depth of 10 to 12 cm of the soil; and/or (2) the increased spatial variability in 2003 after manure application (Figure 3.4).

Table 3.5 The ASP for different landform segments in fall 2003 (bma and ama) and in fall 2004 (mean value of six samples for each landform segment)##.

	Mean ASP (mg P kg^{-1} of soil)#			
	FS	BS	SH	F/P Value¶
Fall 2003 (bma)	6.8^{aA} (41%)	0.6^{cA} (62%)	4.0^{bA} (53%)	$14.1/3.5\times10^{-4}$
Fall 2003 (ama)	7.0^{aA} (63%)	3.1^{aA} (35%)	12.1^{aAB} (83%)	$3.0/7.8\times10^{-2}$
Fall 2004	14.7^{aB} (21%)	10.1^{aB} (70%)	19.1^{aB} (37%)	$3.4/6.2\times10^{-2}$
F/P Value¶	$10.0/1.7\times10^{-3}$	$8.6/3.2\times10^{-3}$	$6.5/9.2\times10^{-3}$	

CV values are reported in parenthesis.# Means with same letters are not significantly different at α = 0.05. Lower case letters are used for mean comparison between columns and upper case letters are used for mean comparison between rows. ¶ From ANOVA table. F, F statistics from ANOVA table; P, probability value for the F statistics from ANOVA table.

By fall 2004, the mean ASP concentration of each landform segment had increased from the concentrations observed in fall 2003 after manure application (Figure 3.5). Mean ASP concentrations in fall 2004 were significantly different from the concentrations observed in fall 2003 (bma and ama) at the FS and the BS (Table 3.5).

The increase in ASP by fall 2004 could be due to the processes such as (1) liberation of ASP in soil by mineralization of applied manure, OM and plant residues, (2) desorption and dissolution and (3) resulting effect of loss and gain of soil P due to soil erosion (i.e. tillage and water erosion) and deposition respectively. However, water and tillage erosion could not be a significant process in this landscape since the average slope was 2.7% and reduced tillage was in use. Jones et al. (2001) report that slopes greater than 3% increase the risk of soil erosion and can lead to increases in nutrient and sediment loading to surface waters. Therefore, the increase in ASP is likely due to liberation of ASP in soil by mineralization, desorption, and dissolution.

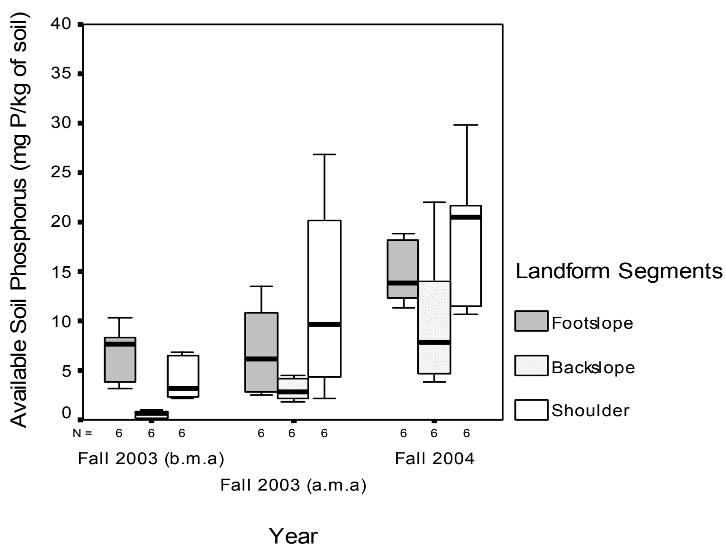

Figure 3.4 Box plots for ASP concentrations for different landform segments in fall 2003 (bma and ama) and in fall 2004. (*The line in the middle of the box is the median value and the box encloses the data points between the 25th and 75th quartile. The whiskers encompass the range of non-outlier data for the landform segments*).

The ASP at the SH in the fall of 2004 was not significantly different from the concentration observed in fall 2003 ama. This is most likely due to the high spatial variability of ASP concentrations observed immediately after manure application in fall

2003 (Figure 3.4). The amount of OM mineralization should have been similar for the BS and the SH since they had similar Org C and moisture contents.

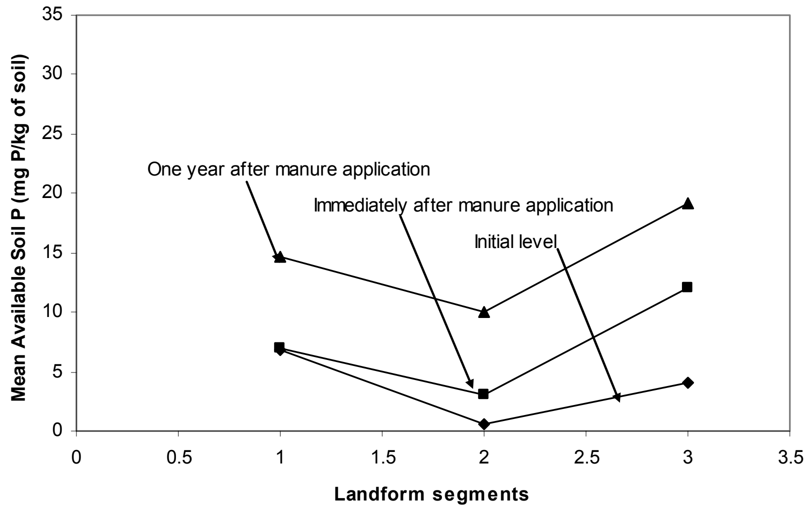

Figure 3.5 Variation of mean ASP concentration in the fall across the landscape before and after manure application and one year after manure application.

3.6.3.2 Variation of available soil phosphorus with the landform segments

The ASP concentrations vary with the landform segments (Figure 3.4 and Table 3.5). In fall 2003 (bma) the lowest ASP concentration (1 mg P kg^{-1} of soil) was at the BS while the highest ASP concentration (7 mg P kg^{-1} of soil) was at the FS. ASP concentrations increased in the sequence of BS <SH < FS. These ASP concentrations are significantly different between the landform segments (Table 3.5). The ASP concentrations in fall 2001 (before any manure application for this field) for the same landform segments of the site showed the same distribution pattern of BS <SH < FS (data are not reported here). This pattern could have resulted from the agronomic and hydrological processes taking place in the landscape. Soil P is not readily soluble in water and is attached to the soil particles. Therefore, soil redistribution over the landscape should be able to explain the ASP distribution in the landscape and this is especially true as any effects of tillage or water erosion for this site, should be made more evident by our sampling depth, surface 5 cm.

The mean ASP in 2003 ama was not significantly different between the landform segments (Table 3.5). Therefore, hog manure injection resulted in a new distribution pattern of mean ASP (as compared to bma) between the landform segments (SH = BS = FS). Mean ASP concentrations in the fall 2004 (one year after manure application) were not significantly different between the landform segments (Table 3.5).

3.6.4 Soil nitrate

The mean soil NO_3^- concentrations between landform segments were not significantly different in fall 2003 bma. Therefore, soil NO_3^- had a distribution pattern of SH = BS = FS (Table 3.6) in the landscape. As soil NO_3^- is readily water soluble, its distribution in the surface 5 cm soil layer could have been influenced by water distribution in 2003 (Table 3.4). Furthermore, the high spatial soil NO_3^- variability (Figure 3.6) within the FS and the BS could have prevented the significant difference between the landform segments.

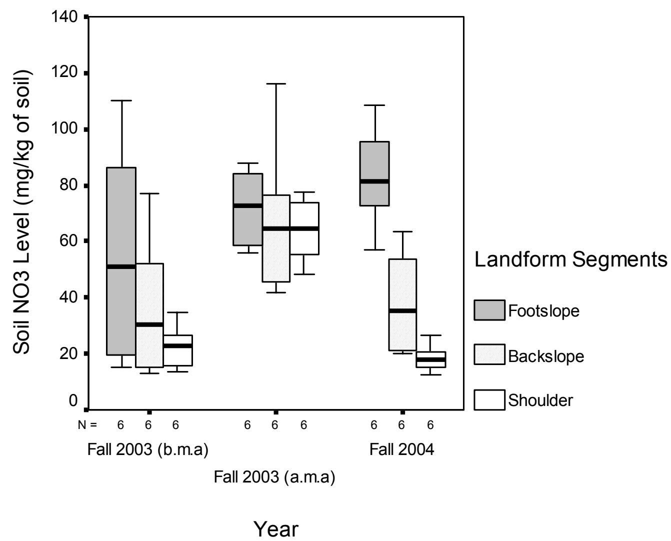

Figure 3.6 Box plots for soil NO_3^- concentrations for different landform segments in fall 2003 (bma and ama) and in fall 2004. (*The line in the middle of the box is the median value and the box encloses the data points between the 25th and 75th quartile. The whiskers encompass the range of non-outlier data for the landform segments*).

Table 3.6 Mean soil NO_3^- for different landform segments in fall 2003 (bma and ama) and in fall 2004[##].

	#Mean Soil NO_3^- - mg NO_3^- kg^{-1} of soil			
	FS	BS	SH	F/P Value¶
Fall 2003 (bma)	55.5^{aA} (70%)	36.4^{aA} (67%)	22.8^{aA} (34%)	2.3/1.3×10^{-1}
Fall 2003 (ama)	72.0^{aA} (20%)	68.3^{aB} (39%)	64.1^{aB} (17%)	0.8/7.6×10^{-1}
Fall 2004	82.8^{aA} (22%)	38.3^{bA} (45%)	18.4^{cA} (27%)	30.3/5.4×10^{-6}
F/P Value¶	1.7/2.1×10^{-1}	3.5/5.0×10^{-2}	56.4/1.0×10^{-7}	

CV values are reported in parenthesis.# Means with same letters are not significantly different at α = 0.05. Lower case letters are used for mean comparison between columns and upper case letters are used for mean comparison between rows. ¶ From ANOVA table. F, F statistics from ANOVA table; P, probability value for F statistics from ANOVA table.

Soil NO_3^- concentrations of the surface 5 cm soil layer increased significantly following manure application (2003 ama) only at the BS and the SH by 32 and 41mg of NO_3^- kg^{-1} of soil respectively. The mean soil NO_3^- concentrations of 5 cm soil layer in fall 2003 ama were not significantly different between the landform segment and still had the distribution pattern of SH = BS = FS (Table 3.6).

In fall 2004, the mean soil NO_3^- concentrations for the landform segments were significantly different from each other and had a distribution pattern of SH < BS < FS (Table 3.6). This distribution pattern was similar to the distribution pattern of TN (Table 3.3). During the 2004 growing season the N supply on the FS and the BS must have been in excess of crop requirements. Wet and cooler summer conditions of 2004 could have been favorable for mineralization. Further, in fall 2004, the FS had significantly higher soil moisture than the SH and the BS (Table 3.4). These conditions could have created significant differences in NO_3^- concentration between the landform segments.

By fall 2004, the SH and the BS had lost soil NO_3^- while the FS had similar soil NO_3^- relative to the concentrations observed in fall 2003 ama. Fall 2004 NO_3^- concentrations for the SH, and the BS have changed by -46 and -30 mg NO_3^- kg^{-1} of soil respectively since the manure application in fall 2003. Possible reasons for soil NO_3^- loss from the SH and the BS could be attributed to (1) crop uptake (2) low OM mineralization and/or (3) NO_3^- loss due to leaching and denitrification. Although crop uptake, leaching and denitrification would have also occurred on the FS, mineralization appears to have been sufficiently high to compensate for the losses.

Soil NO_3^- concentrations in fall 2004 (one year after the manure application) were not significantly different from that of fall 2003 bma for each landform segment (upper case letters, Table 3.6). The NO_3^- resulting from the hog manure injection appeared to have been utilized by the crop, lost by denitrification or leached below the sampling depth (5 cm). Therefore, soil NO_3^- level of the top 5 cm soil layer was stable with time.

3.6.5 Soil ammonium

In fall 2003 bma, the FS had the highest NH_4^+ concentration while the SH and BS had the lowest concentrations of soil NH_4^+ (Table 3.7 and Figure 3.7). This distribution pattern was very similar to that of TN, TC and Org C (Table 3.3). The higher NH_4^+ concentrations at the FS was likely due to the higher OM content which releases NH_4^+ by mineralization.

Table 3.7 Mean soil NH_4^+ for different landform segments of the site in fall 2003 (bma and ama) and in fall 2004$^{\#\#}$.

	$^{\#}$ Mean Soil NH_4^+ - mg NH_4^+ kg^{-1} of soil			
	FS	BS	SH	F/P Value¶
Fall 2003 (bma)	5.7^{aB} (13%)	4.9^{bB} (10%)	4.0^{bB} (15%)	$15.0/2.6\times10^{-4}$
Fall 2003 (ama)	247^{aA} (51%)	147^{aA} (50%)	246^{aA} (64%)	$1.3/2.9\times10^{-1}$
Fall 2004	8.7^{aB} (26%)	5.8^{bB} (35%)	4.1^{bB} (21%)	$9.3/2.3\times10^{-3}$
F/P Value¶	$22.1/3.3\times10^{-5}$	$22.6/2.9\times10^{-5}$	$14.1/3.4\times10^{-4}$	

$^{\#\#}$ *CV values are reported in parenthesis.*$^{\#}$ *Means with same letters are not significantly different at* α = *0.05. Lower case letters are used for mean comparison between columns and upper case letters are used for mean comparison between rows.* ¶ *From ANOVA table. F, F statistics from ANOVA table; P, probability value for F statistics from ANOVA table.*

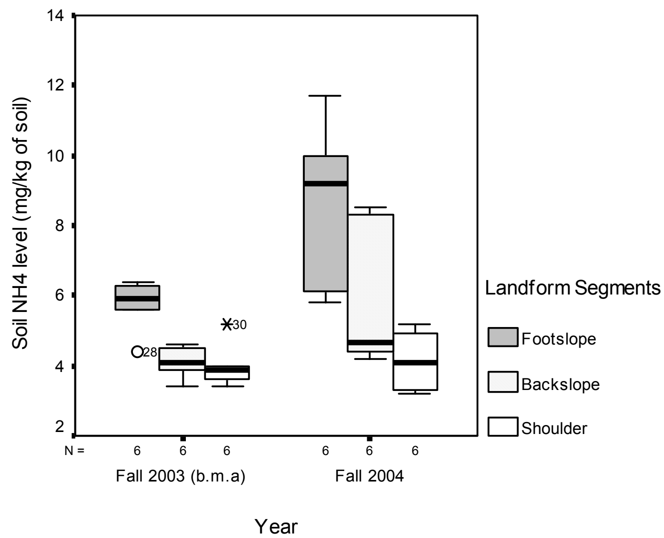

Figure 3.7 Box plots for soil NH_4^+ concentrations for different landform segments in fall 2003 bma and in fall 2004. (*The line in the middle of the box is the median value and the box encloses the data points between the 25th and 75th quartile. The whiskers and outlier symbols encompass the range of non-outlier data for the landform segments*).

Hog manure application significantly increased the soil NH_4^+ concentration in all landform segments (Table 3.7). In fall 2003 after manure application, all landform segments had very high NH_4^+ concentrations compared to the concentration observed before manure application and these concentrations were not significantly different between the landform segments. On the SH, manure application increased the NH_4^+ concentration by a factor of more than 60.

One year after the manure application (fall 2004), soil NH_4^+ concentrations showed the distribution pattern and values observed in fall 2003 bma. Reduction of soil NH_4^+ concentration between fall 2004 and fall 2003 ama from landform segments can be attributed to: (1) crop uptake; (2) nitrification; (3) leaching losses; and/or (4) immobilization and volatilization.

3.7 Conclusions

In fall 2004, the FS had higher TN, TP, TC and Org C in the top 5 cm soil layer than in the other two landform segments. The SH and the BS were homogeneous in terms of TP, TC, and Org C while these two segments were different in terms of TN. Soil moisture contents of first 5 cm layer of the soil also did not vary between the landform segments except for the FS in fall 2004.

For the undulating landscape in this study, ASP concentrations prior to manure application in the fall of 2003 varied with landform segments in the order of BS < SH < FS. Hog manure injection did not immediately increase the ASP concentration in top 5 cm layer. However, the ASP concentration of the surface 5 cm layer of soil in the FS and the BS increased significantly one year after the manure injection and decreased the variability of ASP between the landform segments (i.e. SH = BS = FS). The ASP in the top 5 cm soil layer was not stable with time.

In fall 2003, the landform segments were homogeneous in terms of NO_3^- in the top 5 cm soil layer perhaps because of the dry summer conditions which resulted in homogeneous soil moisture conditions across the landscape. The distribution pattern of soil NO_3^- in fall 2004 (one year after the manure application) followed the distribution pattern of SH < BS < FS. In the absence of freshly applied manure, soil NH_4^+ showed a consistent distribution pattern in the two falls. The SH and the BS segments were homogeneous in term of NH_4^+ concentrations in both falls. The FS segment had a significantly higher NH_4^+ concentration than the other two landform segments. Hog manure injection generally increased both NO_3^- and NH_4^+ concentrations in the top 5 cm layer even though hog manure was injected to a depth of 10-12 cm. However, the increase in soil NO_3^- and NH_4^+ concentrations immediately after the manure application was not observed one year later. Both NO_3^- and NH_4^+ were stable with time.

3.8 Acknowledgements

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CHAPTER 04

Influence of slope position on snowcover characteristics and snowmelt runoff in a small closed catchment in an undulating landscape.

4.1 Abstract

The spatial variability of snow cover characteristics and snowmelt runoff generation at three different landform segments in a closed drainage basin in the Canadian prairies were studied for two years. Snowmelt infiltration at upslope areas of the small depression was also estimated using a water balance approach at the end of the snowmelt runoff period.

The average snow depth for each landform segment, at the peak snow accumulation and before the onset of melt, was lowest at the shoulder and greatest at the footslope. The footslope had significantly greater snow depth than the other two landform segments. However, the significance of the difference in snow depth between the backslope and the shoulder varied with the year. The pre-melt snow density did vary between the landform segments. The pre-melt SWE increased in the down slope direction having the lowest in the shoulder and backslope and the highest in the footslope in 2005.

The average of the daily snowmelt runoff from the closed plots in the 2004 snow melt period (3.47×10^{-3} $m^3m^{-2}d^{-1}$) was significantly lower than that in 2005 spring melt (12.7×10^{-3} $m^3m^{-2}d^{-1}$). The average daily snowmelt runoff and the average of total snowmelt runoff from 1 m^2 plots did not vary between the shoulder and the backslope. Further, irrespective of the year, the closed plots in both the backslope and the shoulder produced approximately the same proportion of runoff on average from SWE. In both snowmelt periods, the average runoff values at the backslope estimated using open plots were significantly higher than the average runoff values estimated using closed plots because of the larger contributing areas for the open plots.

Total snowmelt runoff to the depression varied with the year. The total runoff from the entire watershed was 31% and 91% (of total water input) respectively for 2004 and 2005. The total infiltration over the watershed was 69% and 9% (of total water input) respectively for 2004 and 2005. High infiltration in 2004 was likely due to dry fall soil moisture condition and cracks and macro-pores created during manure injection in the fall. Of the three landform segments, the shoulder was the biggest contributor (30% and 43% of total runoff respectively in 2004 and 2005) to the total snowmelt runoff of the watershed in both years. The backslope contributed the least (13% and 16% of total snowmelt runoff respectively in 2004 and 2005).

Keywords: Snowmelt runoff, infiltration, Snow water equivalent, landscape position.

4.2 Introduction

Closed depressions are common topographic features in the landscape of Canadian prairies. They receive runoff water from the surrounding lands during snowmelt and heavy rainfall. These depressions are important and have increasingly recognized functions with regard to surface water storage, quality of water (surface and ground), ground water recharge, contaminant transport and ecology (van der Kamp and Hayashi, 1998; Hayashi et al., 2003). The processes by which water and solute are exchanged between the depression or a similar water body (such as a lake or a wetland) and the surrounding land areas should be understood for better understanding and improved prediction of these functions. Among these processes, snowmelt runoff to the depressions is one of the most important processes governing the hydrology and the water quality of prairie depressions. Therefore, snowmelt runoff generation at different landform segments surrounding the depressions and importance of landform segments on water balance of these depressions must be realized. Though snowmelt runoff has been studied extensively, the knowledge on snowmelt runoff generation at different landform segments and their relative importance on water balance are still missing. This knowledge is very important in the understanding of snowmelt runoff process and snowmelt runoff water quality in these depressions on the Canadian prairies.

Snow cover characteristics have been studied extensively (U.S. Army Corps Engineers, 1956; Evans et al., 1989; Pomeroy and Gray, 1995; Lapen and Martz, 1996; Marsh, 1999). However, these studies have focused on the larger scales such as watershed or regional. Therefore, studies on snow cover characteristics at different landform segments are limited. With a study of snow depth and topography in a prairie environment, Lapen and Martz (1996) demonstrated that simple relationships between snow accumulation and topographic descriptors of slope position were not evident. With a 100 m grid scale, Marchand and Killingtveit (2001) showed that there was no strong relationship between terrain characteristics (i.e. slope, aspect, curvature and elevation) and snow depth. However, Evans et al. (1989) found correlations between snow depth and aspect and between snow depth and vegetation at an arctic foothills site in Alaska. Pomeroy and Gray (1995) reported that differences in snow accumulation pattern at the micro-scale (i.e. characteristic distances of 10 to 100 m) resulted from differences in air flow pattern and transport. Significant redistribution of snow could occur with blowing snow resulting in exposed hill tops due to significant scouring, and large depositions of snow at protected areas (Marsh, 1999). Lapen and Martz (1996) observed that most of the deeper snow packs were limited to the leeward slopes and water ways and the shallower snow drifts were located on the windward slopes and exposed level areas.

Snow melting and snowmelt runoff processes have been studied by a number of researchers (Bengtsson, 1985; Granger and Gray, 1990; Kane et al., 1991; Shook et al., 1993; Harms and Chanasyk, 1998; Westerstrom and Singh, 2000; Gray et al., 2001; Moncrief et al., 2005). The process of snow melting does not occur uniformly within a watershed and differences in the timing and the amount of snowmelt runoff from the hillslope plots with similar snow accumulations and snow density characteristics have been reported by Harms and Chanasyk (1998). Bengtsson (1985) reported a considerable lag between melt and runoff, except on steep slopes. Harms and Chanasyk (1998) reported a high spatial variability in the timing and the amount of snowmelt runoff between replicated plots at similar slope positions and between the slope positions along the same aspect. Westerstrom and Singh (2000) reported that during the snowmelt season, the snowmelt usually began around 07:00 hours, reached its peak around 15:00 hours and ended around 22:00 hours lasting for about 15 hours for the experimental plots in Lulea, Sweden. Westerstrom and Singh (2000) further showed the variability in daily snowmelt runoff between years and the surface. However, studies on snowmelt runoff generation at different landform segments and snowmelt run-on (i.e. runoff from the upslope areas above the location concerned) to different landform segments are absent.

Therefore, the purpose of this study was to (1) investigate the spatial association between snow cover characteristics (i.e., snow depth, snow density and SWE) and landform segments; (2) investigate the spatial association of snowmelt runoff generation and run-on with landform segments; and (3) understand the relative importance of landform segments on the water balance of the depression at the end of snowmelt runoff period. The study was conducted in a closed drainage basin in an undulating agricultural landscape on the Canadian prairies. Since the snow cover is constantly changing with time, snow cover characteristics are studied at the time of peak snow accumulation and during the early stage of spring snowmelt.

The knowledge of spatial variability in snowcover characteristics and snowmelt runoff across the landscape can be used to study snowmelt runoff water quality. In conjunction with soil residual nutrient distributions in late fall, the data collected in this study will facilitate: (a) the identification of critical source areas (CSA) that contribute nutrients to the surface water resources through snowmelt runoff; (b) the understanding of factors controlling snowmelt runoff water quality; and (c) the understanding of the relative importance of landform segments on water balance of the depressions in Canadian prairies. This will be useful in the design and implementation of control measures that reduce or prevent soil nutrients from contributing to depressions, and similar features like lakes and wetlands in this region, through snowmelt runoff.

4.3 Literature Review

4.3.1 Snow cover characteristics and distribution

An exponential decrease in snow density occurs as the air temperature during snowfall decreases below freezing (U.S. Army Corps Engineers, 1956). The density of freshly fallen snow can vary widely depending on the amount of air within the lattice of the snow crystals (Pomeroy and Gray, 1995). The snow density increases rapidly following deposition due to temperature and water vapour gradients, crystal settlement and wind packing, and this process is termed as metamorphism (Pomeroy and Gray, 1995). Snow density of the snow pack also varies during snowmelt due to storage and loss of melt water.

Pomeroy and Gray (1995) reported that the seasonal snow cover depth increased with increasing elevation in a mountainous region and this was attributed to a successive increase in the number of snowfall events and a decrease in evaporation and melt. However, the rate of SWE increase with elevation could vary extensively from year to year. Pomeroy and Gray (1995) further reported that the difference in snow accumulation pattern at the micro-scale (i.e. characteristic distances of 10 to 100 m) was due to the variation in air flow pattern and transport. Blowing snow could cause significant redistribution of snow, resulting in exposed hill tops due to significant scouring, and large depositions at protected areas (Marsh, 1999). Snow redistribution is commonly governed by the wind speed and direction, the surface roughness imposed by vegetation, surface morphology, orientation of obstacle to the wind, and the position of obstacles relative to each other (Pomeroy and Gray, 1995; Lapen and Martz, 1996). Lapen and Martz (1996) observed most of the deeper snow drifts on the leeward slopes and in water ways and the shallower drifts on the windward slopes and in exposed level areas. They further reported that stubble sites captured more snow than fallow sites.

Sublimation of wind transported snow, which is a function of wind speed, air temperature, humidity, particle size and solar radiation, can significantly reduce snow cover (Marsh, 1999). The sublimation reduces the snow cover at the end of the winter and thereby reduces snowmelt runoff. Estimated seasonal snow transport and sublimation for 15 locations in western Canada showed that sublimation used up 15% to 40% of seasonal snowfall (Woo et al., 2000).

During melting, evaporation reduces the water available in the snow pack for infiltration and surface runoff. However, Bengtsson (1980) reported that evaporation from snowpack during snowmelt was a minor component of the mass balance equation, usually averaging less than 1 mm per day or 10 to 20 mm for the whole snow ablation period.

For an arctic foothills site in Alaska, Evans et al. (1989) found a correlation between snow depth and aspect and a clear correlation between snow depth and vegetation. In a study of snow depth and topographic descriptors in a prairie environment, Lapen and Martz (1996) observed no apparent simple relationships between snow accumulation and descriptors of topographic slope position. In a mountain watershed, Elder et al. (1998) could explain the 60-70% of variance in the snow depth measurements using net radiation, elevation and slope. With a 100 m grid scale, Marchand and Killingtveit (2001) found that there was no strong relationship between terrain characteristics (i.e. slope, aspect, curvature and elevation) and snow depth.

4.3.2 Snow melting and snowmelt runoff

Energy exchanges at the air-snow and snow-soil interface, and the physical characteristics of the snow pack mainly control the process of snow melting (Kane et al., 1991).

Incoming solar radiation is the dominant force in the energy balance equation, governing the timing of melt and rate of snowmelt (Granger and Gray, 1990). In open areas, net radiation and sensible heat are the primary fluxes that control the melt process

(Granger and Gray, 1990). The bare ground within a snow field could significantly alter the energy balance. Bare ground can absorb large amounts of solar radiation and heats more quickly because bare ground has a lower albedo than snow. Advection of heat energy from the bare ground and the turbulent transfer of latent and sensible heat to adjacent snow covers increase the rate of snow melting (Shook et al., 1993). In a study done in a small watershed in the west-central part of Saskatchewan in the Canadian Prairies, Shook et al. (1993) reported that turbulent melt (i.e. melt mainly due to sensible heat exchange) was dominant in areas with small snow patches throughout the season, but in larger snow fields, radiation melt was dominant early in the season and turbulent melt later in the season as the snow fields decreased in area. In regions where elevation has no significant influence on melting, the maximum rates of melt and runoff occur when the land is partially covered with snow (Shook et al., 1993).

Both timing of melt and the rate of snowmelt are primarily governed by the net short-wave component of radiation; whereas the timing of runoff water release from the snow cover is affected by the net long-wave flux because of its influence on night-time refreezing and thus on the internal energy status of a snowcover (Granger and Gray, 1990). The snowmelt process does not occur uniformly within a watershed. Harms and Chanasyk, (1998) observed the existence of major differences in the timing and amount of runoff from the hillslope plots with similar snow accumulation and snow density characteristics. There could be differences in snowmelt between south facing and north facing slopes due to the fact that south facing slopes are more directly exposed to daily incoming solar radiation than are the north facing slopes (Harms and Chanasyk, 1998).

There are number of sub processes involved in the snowmelt runoff generation from a snow cover. The surface melt is the first process. Usually, the surface melt is unevenly distributed over the day and reaches a pronounced peak melt during the day (Bengtsson, 1985). Meltwater moves down through the snowpack, but no water is released until the liquid content of the snow pack is above the water holding capacity (WHC) of the snow pack. A number of factors such as ice layers, structure of the snow pack, thickness of the snow pack, and moisture content govern the percolation of melt water through the snow pack. Bengtsson (1985) observed considerable lag between melt and runoff except on steeply sloping land. Harms and Chanasyk (1998) reported high spatial variability in the timing and amount of hillslope snowmelt runoff between plots at similar slope positions and between slope positions with the same aspect. Westerstrom and Singh (2000) reported that daily snowmelt runoff for the whole snowmelt season varied with the year and the surface.

Melt water that reaches the ground surface may either infiltrate or runoff. In northern regions, the infiltration capacity of frozen soils determines the snowmelt runoff. Soils have low hydraulic conductivity when they are frozen and as a result, prairie conditions produce significant snowmelt runoff in the early spring (Hayashi et al., 2003).

Snowmelt infiltration also varies with tillage system. In a study of tillage effects on runoff and erosion in the Peace River region of Canada, van Vliet et al. (1993) indicated that snowmelt runoff was higher in high residue systems such as zero tillage than in conventional tillage systems.

4.3.3 Snowmelt infiltration

Annual climatic variability, land use, tillage practices, and spatial variability of soil physical properties determine the partitioning of snowmelt into runoff and infiltration in a given physiographic region (Moncrief et al., 2005).

Infiltration of melt water into frozen soil is a complex process. It involves coupled heat and mass flow with phase changes. Factors such as soil thermal and hydraulic properties, soil temperature, the soil moisture regime and the quantity and rate of water release from the snow pack influence snowmelt infiltration into frozen soils (Westerstrom and Singh, 2000; Gray et al., 2001).

Kane (1980) demonstrated an inverse relationship between infiltration and frozen soil moisture. In the absence of cracks and other macro-pores in the soil profile, the soil moisture content of a frozen soil is the major physical property governing absorption and transmission of water by the soil (Granger et al., 1984). Part or all of the water entering a frozen soil will refreeze. Granger et al. (1984) reported that this amount is a function of the energy status of both soil and water, the amount of free water available, and the energy exchange between the media. Hinzman and Kane (1991) observed that all downward movement of water occurred within the upper 10 cm of a highly organic soil layer at the surface.

Kane et al. (1991) observed that only a small volume of melt water was needed to refreeze and release latent heat to warm the soil to 0°C. Westerstrom and Singh

(2000) reported that the latent heat released by refreezing was very effective at warming the snow pack and upper soil horizons.

Stähli et al. (2004) used tracer experiments in southern Switzerland to demonstrate that a frozen soil layer impedes snowmelt infiltration rather than prevents it. Although the snowmelt water transfers heat to the soil, the soil surface remains initially cold. This could create an ice layer on the soil surface, which impedes snowmelt infiltration and increases snowmelt runoff. Stähli et al. (2004) reported that such an ice layer could have a thickness of one to a few cm. They further measured 20 to 25% runoff from the soil surface with a basal ice layer and reported 100% infiltration of snowmelt outflow into the soil in the absence of a basal ice layer.

Westerstrom and Singh (2000) reported that the rate of snowmelt infiltration during a given snowmelt event increases with time, reaches a peak and then declines. They attributed this rate increase to the increasing availability of snowmelt water with the progression of the snowmelt event and the decline in infiltration rate after the peak was attributed to the declining space in the soil to absorb water. Westerstrom and Singh (2000) reported that at the beginning of the melt season, the melt rate was higher than the infiltration capacity of the frozen soil. However, as snowmelt water infiltrates, it helps the soil to thaw. The thawing soil can absorb more water. As a result, the rate of snowmelt infiltration increases as the amount of infiltration increases (Westerstrom and Singh, 2000).

The amount of infiltration into frozen soil is further influenced by the type and extent of soil frost and the type and extent of vegetative cover (Granger et al., 1984). For non cracking soils, Granger et al. (1984) observed that the average depth of meltwater penetration during spring snowmelt was about 26 cm. Granger et al. (1984) report that soils in the prairies are usually frozen to a depth of 1.5 m and remain frozen until melt is finished.

Mineral soils, frozen to a depth of less than 15 cm, act the same way as an unfrozen soil does (Komarov and Makarova, 1973). If a soil is frozen beyond a depth of 60 cm, freezing to a greater depth has no effect on infiltration (Komarov and Makarova, 1973).

Van der Kamp et al. (2003) reported much higher infiltrability of the frozen soil in a grass field than in a cultivated field at the St. Denis National Wildlife area in the prairie region of southern Saskatchewan, Canada and this difference was attributed to the fact that grassed soil had a well developed macro-pore network. Tillage and surface residue also influence soil freezing rate and depth and hence water infiltration.

The surface residue helps to reduce the depth of soil freezing (McCool et al., 2000). The heat capacity under residues is higher because of reduced heat loss at night and increased soil water content, and thus freezing depth is reduced. Surface residue can also reduce air movement near soil surface and standing stubble can trap snow, insulating the soil surface (McCool et al., 2000).

Johnson and Lundin (1991) attributed initially high snowmelt infiltration into frozen soils to macro-pores or over-winter soil moisture deficits. However, initially high infiltration rates can quickly drop to a rate controlled by the amount and continuity of unfrozen water in small soil pores or unfrozen water in a film adhering to soil particles (Burn, 1991). Steenhuis et al. (1997) reported that snowmelt infiltration into frozen soils was primarily restricted to macro-pores.

With field data collected from frozen, unsaturated agricultural soils in the Canadian prairies during snow ablation, Zhao et al. (2002) demonstrated a poor association between the amount of infiltration of melt water from seasonal snow cover and soil texture. Zhao et al. (2002) observed small differences in the cumulative amounts of infiltration among soils of widely different textures.

4.4 Site Characteristics

The study site, chosen within one farm field as being representative of the local landscape, is a small closed drainage basin of 8249 m^2 with an average slope of 2.7%. The site is located near the town of Elstow (52° 02' N, 106° 06' W), 55 km east of the city of Saskatoon, Saskatchewan, Canada. During the spring melt season, snowmelt runoff generated within the watershed accumulates in a central depression (408 m^2) until it completely infiltrates over several weeks. The area, in which the study site is located, has an undulating landscape with local small hilltops and depressions consisting of fine textured lacustrine material over till. Ephemeral runoff water accumulation in these depressions plays an important role in the hydrology and ecology of the area, by holding runoff water, recharging soil moisture and ground water (Hayashi et al., 2003). The soil is classified as an Orthic Dark Brown Chernozem of the Elstow Association (Acton and Ellis, 1978) consisting of medium to moderately fine textured, moderately calcareous, clayey glacio-lacustrine deposits. Texture of the upper 15 cm of soil is clay loam to silty clay. Reduced tillage practices were used on this field with no fall cultivation except in 2003 when hog manure was injected to a depth of 10-12 cm in the east to west direction using knife openers at a 40 cm spacing followed by a compaction wheel that closed the slots. Prior to the study, the field had been under cereal crop production (mainly cereal grains such as wheat and oilseeds such as canola). Canary seed (*Phalaris canariensis*) and wheat (*Triticum aestivum* L.) were grown in 2003 and 2004 respectively. Average stubble (remained after fall harvest) height was about 15 cm in both years. According to visual observations, the stubble density was higher in the FS than that of the BS and the SH. Crops had been planted in rows running in the east-west direction in both years. The average distance between the rows was 14 cm. This small watershed is in the middle of a cultivated field and there are no obstructions such as large trees, buildings anywhere within 500 m of the site.

A meteorological station, installed 0.5 km south of the site, recorded temperature, wind speed, relative humidity, solar radiation and rainfall data from 2002 to Summer 2005. For comparison purposes climatic normals (1971-2000) from the town of Viscount, (51° 57’ N, 105° 37’ W) about 30 km to the east of the site, were used (Environment Canada, 2005). The mean annual air temperature at Viscount was 2.5 °C, with monthly mean temperatures of -16.8 °C in January and 18.1°C in July (1971-2000).

Monthly air temperatures are below 0 °C from November through March; therefore, a hydrological year is defined starting on 1 November and ending on 31 October (Hayashi et al., 1998). A hydrological year consists of a winter (November to March), a spring (April and May), a summer (June to August) and a fall (September and October). The mean annual precipitation at Viscount is 412 mm, of which 84 mm (20 % of mean annual precipitation) occurs in the winter, mostly as snow, 184 mm falls during the three summer months of June, July and August and the remaining 63 mm occurs during the fall (1971-2000 climate normal).

This chapter presents the results of the analysis for snow distribution and snowmelt runoff at different landform segments for winters 2003/2004 and 2004/2005 (termed as winter 2004 and winter 2005 respectively in this study).

4.5 Materials and Methods

The site was divided into landform segments (i.e. SH, BS, FS and depression) using a digital elevation model (DEM) derived from topographic survey data for the site. The SH (5606 m^2), the BS (1386 m^2) and the FS (849 m^2) segments were selected for this study as they are the upslope areas contributing runoff to the depression (408 m^2). Six sampling transects were established, each running from the FS to the SH radiating outwards from the depression in the directions of NE, E, SE, SW, W, and NW. Three sample locations per transect were picked such that each landform segment was represented. Random samples within landform segments were not used with the intention of minimizing the disturbance to the snowcover during the winter measurements and to facilitate easy access during the spring sampling.

Hillslope runoff was measured using square runoff plots (1 m^2 each) installed at each sample location in the fall 2003 and fall 2004 before the soil was frozen. Each runoff plot in the BS and the FS consisted of two 1 m^2 plots placed one below the other and in the down slope direction (Figure 4.1). The upper runoff plot had only 3 sides and was open to the upslope side to catch run-on (i.e. runoff from the upslope areas above the location concerned) to the sampling location and was referred as “open plot”. The lower runoff plot was closed on all 4 sides and was referred as “closed plot”. All runoff plots at the SH were closed plots. Open plots were not established at the SH as it was assumed that there was no run-on to these sampling locations being at the edge of the watershed. Within the watershed, the runoff plots were located at the three slope positions and were replicated 6 times (within each landform segment) for a total of 18 closed plots and 12 open plots.

The closed runoff plots were hydrologically separated by metal plates extending 10 cm into the ground and 10 cm above the ground. Runoff from each runoff plot was routed through a pipe into a collection bag (17 L capacity) placed in a hole below the ground surface. Connections between the pipe and the metal plates were sealed using glue to prevent any water leaks through these connections. Each hole was covered with a piece of polyethylene sheet during the winter to avoid snow falling into the hole and subsequently melting. A small drainage channel was made around the holes to avoid runoff water flowing into the hole. Snow and the polyethylene sheet above each hole were removed before melting began. Two snow stakes were installed, at diagonal ends of each runoff plot so that they faced the upslope direction (Figure 4.1). These snow stakes were 2.5 cm wide, 110 cm long wooden sticks with a scale (1 mm divisions up to 1 m) marked on one side of them. Within the watershed 12 snow stakes were located within each landform segment; the SH, the BS and the FS for a total of 36 snow stakes in the watershed.

In 2004, snow depth surveys were conducted on 23 February, 9, 15, 21, 24, 27, 29, 31 March and on 1, 2, 3, 4 April until the snow cover had completely disappeared. In 2005, snow depth surveys were conducted on 3 February, 4, 9, 11, 27, 29, 30, 31 March, and on 1, 2, 3 April. The dates for the snow depth surveys before melting were decided based on either snow fall or warm spells. During each snow survey, the snow depths given on the snow stakes were read from the edge of the watershed using binoculars. The entire watershed and the surrounding fields were completely covered with snow in both winters.

Snow samples were collected using a 61 mm diameter snow survey tube, on 9 March 2004, and 27 March 2005, to calculate pre-melt snow density and SWE. On 9 March 2004, one snow sample from each landform segment along the north-south transect was collected. On 27 March 2005, four snow samples were collected from each landform segment along south, north, west and east transects. During 2005 spring melt, snow samples (referred as post-melt snow samples) were collected every day starting on

29 March 2005, until snow cover disappeared, and one sample for each landform segment along the north transect was collected.

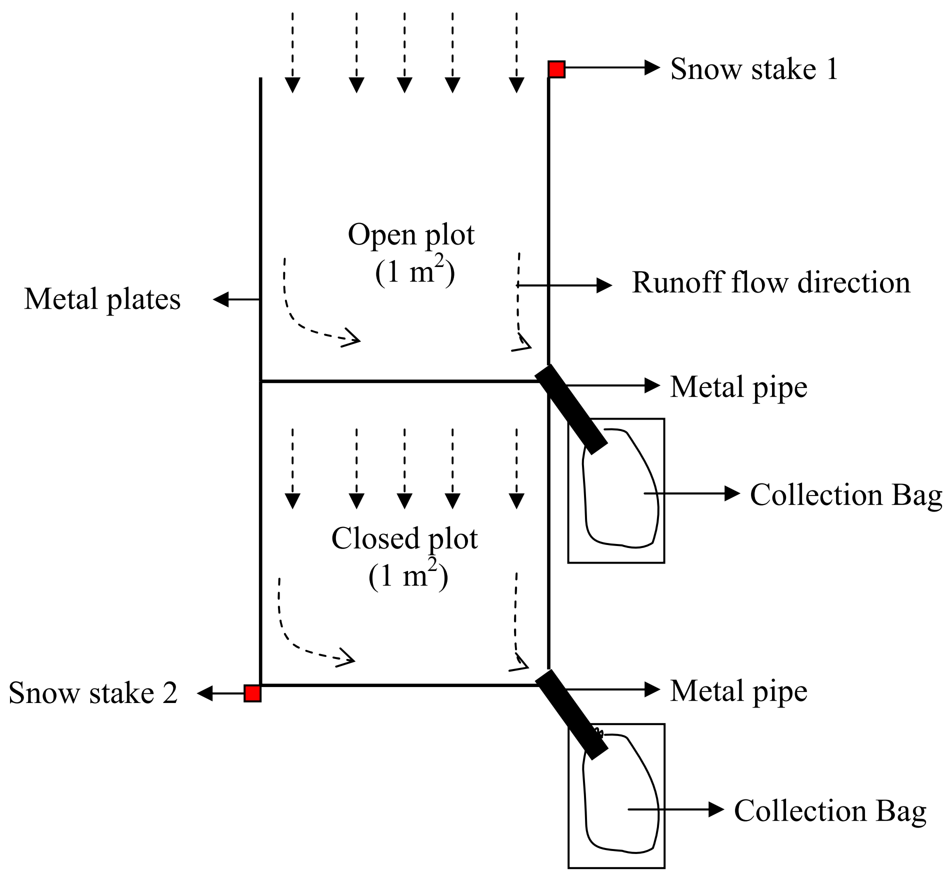

Figure 4.1 A schematic diagram of runoff plots with a closed plot and an open plot placed in a down slope direction at a sampling location.

The volume of runoff within each collection bag was measured daily at each site during spring melt using a measuring cylinder. The spring melt period was defined as the period of sustained melt when most of the surface runoff occurs (however, in both winters, mid winter melting was not observed). Times of runoff volume measurement varied with the day depending on the field and weather conditions. However, most of these measurements were taken during the late afternoon and early evening (e.g., 3 pm-7 pm). A new bag was attached to each pipe once the collection bag with runoff water was detached from the pipe for volume measurement. If runoff water was flowing out from the pipe at the time of bag replacement, the instantaneous flow rate was also recorded by measuring volume of runoff water collected within a given time, usually one minute. When the instantaneous flow rate was judged as high enough to fill half or full of the collection bag within 3-4 hours, runoff volume measurement was done twice a day. The time interval between two measurements on the same plot was 3-4 hours.

The water level of the depression was monitored during the spring melt season with an ultrasonic depth sensor (Campbell Scientific, SR 50), placed 2 m above the ground surface. The volume of water accumulated in the depression was estimated using volume-depth relationship developed from the DEM. As Hayashi et al. (1998) reported, snowmelt runoff, evaporation from the water accumulated in the depression, and seepage under the depression are the major processes governing the water balance of a depression (i.e. volume of water in the depression = Σ water inflow - Σ water outflow) in Canadian prairie. The effective snowmelt runoff (i.e. SWE – infiltration) from all three landform segments was estimated using snowmelt runoff measured using closed plots. The infiltration on the watershed was estimated as the difference between the runoff and SWE. The infiltration under depression was estimated as the difference between the total runoff from the watershed and the total water accumulated in the depression.

Evaporative losses during the melting period were assumed to be negligible. Details of the water balance estimation are given in the section 4.6.6.

The values of snow depths, pre-melt snow density, and snowmelt runoff for each landform segment in both 2004 and 2005 were initially grouped into box plots, which allow both the median and dispersion of values to be visually assessed. The results were tested for normal distribution with Shapiro-Wilk statistics using the *Proc Univariate* function of Statistical Analysis System software (SAS Institute, 1999). Since the data (or log transformed data) from each landform segment approximated a normal distribution, parametric statistics were used to compare snow density and snow depths between landform segments. The results were evaluated using a one-way analysis of variance (ANOVA) using least significance difference (LSD) multiple comparison to assess the significance of the difference between pairs of landform segments. The average snow depths at the peak and at onset of snowmelt for the entire watershed were compared using a t-test for both years. The significance level (α) for all the above tests was set at 0.05.

4.6 Results and Discussion

4.6.1 Meteorology

Snow accumulation during both winters was more or less equal to the long term normal (LTN) snowfall (Table 4.1). The total snow depth (i.e. summation of all the snow falls) recorded at the meteorological station at Saskatoon International Airport for the winter 2004 was 87 cm while it was 91 cm for winter 2005. In winter 2004, approximately half of the total snowfall occurred during March while in winter 2005, it occurred earlier. The average air temperatures for both over-winter periods were similar to the LTN (Table 4.1).

Based on the records at Saskatoon Airport, the study period was characterized by a relatively dry summer and dry fall in 2003 (143 mm and 45 mm respectively) and a normal summer (183 mm) in 2004 followed by a dry fall (32 mm). Summer and fall in 2003 were warmer (17.4 °C and 7.8 °C respectively) than normal temperatures, whereas summer and fall 2004 were cooler (14.2 °C and 6.4 °C respectively) than normal.

Table 4.1 Total snowfall and average temperature from 1 November to 31 March recorded at the meteorological station at Saskatoon International Airport.

	2004 Winter	2005 Winter	LTN[##]
[#]Snowfall (mm)	64	67	63
Temperature (°C)	-10.5	-9.9	-11.3

[#] *Expressed as a depth of water.* [##] *For the meteorological station at Saskatoon International Airport (1971-2000).*

4.6.2 Snow accumulation and distribution

Peak snow depths (37 cm and 33 cm) occurred on 21 March 2004, and on 27 March 2005 respectively in winters 2004 and 2005. The difference in winter conditions (such as temperature fluctuations, wind velocity, wind direction, amount of snow fall, etc.) between the two winters and the timing of snowfall may account for this difference (Pomeroy and Gray, 1995; Lapen and Martz, 1996; Marsh, 1999). In 2004, approximately half of the total snowfall occurred in the month of March, whereas in 2005, most of the snowfall occurred before March. However, the peak snow depth in 2004 was not significantly different from the peak snow depth in 2005 (Table 4.2).

Table 4.2 Summary statistics of snow depths for the watershed at the peak snow depth and at the onset of snowmelt[##].

	2004 $\bar{x}$ (cm)[#]	2005 $\bar{x}$ (cm)[#]	P Value[¶]
At the peak snow depth	37^{aA} (37%)	33^{aA} (41%)	1.3×10^{-1}
At the onset of snowmelt	31^{aB} (43%)	27^{aB} (47%)	2.8×10^{-1}
P Value[¶¶]	2.4×10^{-12}	6.1×10^{-17}	

[##] CV values are reported in parenthesis; $\bar{x}$, mean snow depth; P, probability value. Number of samples was 36 for both 2004 and 2005. [#] *Means with same letters are not significantly different at α = 0.05. Lowercase letters are used to compare snow depth between the columns and uppercase letters are used to compare between the rows.*[¶] *From t-test.* [¶¶] *From paired t-test.*

In both years, snow melting began on 29 March, two days after the average daily temperature rose above zero. Snow depths at the onset of snowmelt in both years were significantly lower than their peak values and the variability had increased compared to that at the time of peak accumulation (higher CV, Table 4.2). The reduction in snow depth could be due to processes such as snow settling, snow ripening, sublimation

(McKay and Gray, 1981) and wind erosion (Pomeroy and Gray, 1995). Variability of these processes over the watershed could have increased the CV of snow depths.

When the peak snow depth and snow depth at the onset of snowmelt were grouped into the landform segments, the CV was reduced from 37-47 % (Table 4.2) to 12-30 % (Table 4.3) indicating greater uniformity of snow depths within each landform segment than in the entire watershed. The magnitude of snow depths at the peak snow depth and at the onset of snowmelt in both winters increased in the down slope direction having the lowest depth at the SH and the highest at the FS. This is probably due to greater snow deposition in the FS and higher snow erosion at the SH due to the variation of airflow pattern and transport (Pomeroy and Gray, 1995). In both winters, the FS had significantly greater snow depth (Table 4.3) than the BS and the SH. At the peak snow depth in winter 2004, snow accumulation in the BS was significantly greater than in the SH but not in 2005 (Table 4.3). A similar result was observed at the onset of snowmelt even though the snow was not as deep (data are not reported here). These differences between the winters could have been caused by the differences in snow redistribution, wind direction and velocity and timing of the snowfall in both winters.

The snow accumulation pattern observed for the landform segments is likely due to the influence of topographic sheltering and surface curvature variables. Lapen and Martz (1996) reported that deeper snow was associated with sites lying below their immediate surroundings and with sites having a greater proportion of local topographic obstacles. Lapen and Martz (1996) further reported that snow depth tends to decrease with slope convexity. Convex slopes are typically associated with the SH where airflow tends to converge and enhance the potential for snow erosion. The FS is associated with concave slopes and is in low lying areas in the landscape. Therefore, the finding of deep snow accumulation at the FS and shallow snowcover at the SH is reasonable. However, in this watershed, slope was not high enough to make the SH and BS significantly different always in terms of snow depth.

Table 4.3 Summary statistics of snow depths for the landform segments at peak snow depths[##].

	$\bar{x}$ (cm)[#]			
	FS	BS	SH	F/P Value[¶]
21 March 2004	54^a (14%)	33^b (16%)	25^c (22%)	$32.6/3.4\times10^{-6}$
27 March 2005	47^a (24%)	29^b (25%)	22^b (21%)	$15.4/2.2\times10^{-4}$

Number of sample sites was 12 for both 2004 and 2005. [##] CV values are reported in parenthesis. $\bar{x}$, mean snow depth at the peak; F, F statistics from ANOVA; P, probability for F statistics from ANOVA. [#] *Means with same letters are not significantly different at $\alpha = 0.05$. Lowercase letters are used to compare snow depths between the columns (landform segments).* .[¶] *From ANOVA table.*

Temporal variation of snow depths for the three landform segments was more or less similar in both winters (Figure 4.2). In both winters, the FS was significantly different from the SH and the BS, while the BS and the SH were similar (the Kruskal-Wallis rank and Wilcoxon rank sum tests were used to compare median values of temporally varied snow depths between landform segments [p = 0.00027 and p = 0.00015 respectively for 2004 and 2005]).

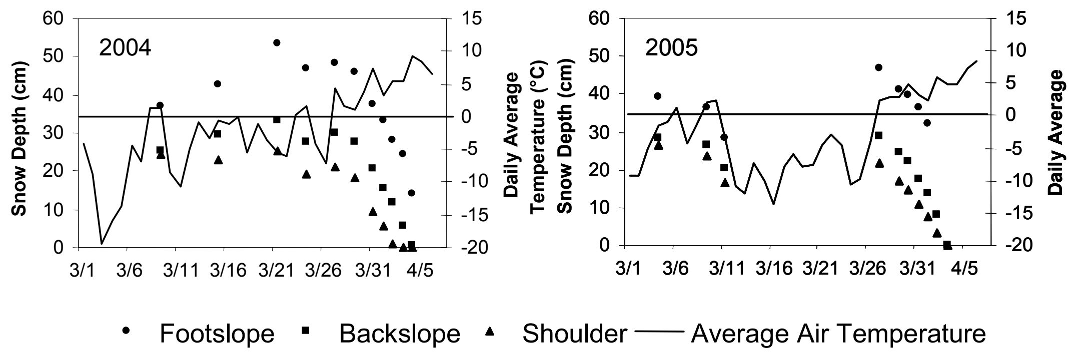

Figure 4.2 Temporal variation of snow depths at landform segments in 2004 and 2005.

In 2004, snow depths for each landform segment showed a gradual increase to the peak snow depths as snow accumulated due to snowfall (approximately half of the total snow fall occurred in March) and snow transport due to wind (Figure 4.2). In 2005, snow depths were not recorded in the middle of March since there was no significant snowfall during that time and most of the snowfall occurred earlier. Therefore, a gradual increase in snow depths was not observed in 2005. During 2005, warm weather at the beginning of March was reflected in snow depth reduction (Figure 4.2) during the same time period. This was likely due to accelerated snow densification and snow ripening due to the warm weather. After the peak snow depths in 2004, the snow depths gradually decreased with time until the onset of snowmelt on 29 March (Figure 4.2) as snow ripened and settled. However, in 2005, the gradual decrease in snow depths due to ripening and settling was not observed clearly as the time interval between the peak snow depth and the onset of snowmelt was short (2 days). In both years, after snowmelt started, snow depths decreased sharply and snow cover disappeared completely within 4 to 5 days.

4.6.3 Snow density and snow water equivalent

In 2005, pre-melt snow density was measured on 27 March 2005, two days before melting began. In 2004, it was measured on 9 March 2004 because of the warm weather between 3 March and 9 March 2004. After 9 March 2004, the average daily air temperature was close to zero between 15 March 2004 and 25 March 2004 (Figure 4.2) and this could have accelerated the metamorphism process thus increasing the snow density. Pomeroy and Gray (1995) reported rapid increases in snow density following snow deposition and a seasonal increase in snow density due to metamorphism caused by the strong temperature gradients that form in shallow snowpacks in Canadian prairies. For this reason, snow density values measured on 9 March 2004 (Table 4.4) do not likely represent the pre-melt snow density before melting in 2004.

Pre-melt snow density did not show any specific pattern of variation with landform segments in either winter. Pre-melt snow density in 2005 did not significantly vary between the landform segments (Table 4.4). Snow density measured on 9 March 2004 could not be tested for significance differences between the landform segments due to lack of replication. The average pre-melt snow density, 298 kg m^{-3} (Table 4.4) observed in 2005 was close to the approximate pre-melt snow density of 300 kg m^{-3} for Canadian prairies reported by Pomeroy and Gray (1995).

The magnitude of pre-melt SWE increased in the down slope direction (Table 4.5). Even though, pre-melt snow density in 2005 was statistically similar among the landform segments (Table 4.4), SWE at the FS was significantly different from that of the SH and the BS while the SH and the BS had similar SWE. This SWE pattern for 2005 was similar to the snow depth pattern observed on 27 March 2005 (Table 4.3), and the correlation between snow depth and SWE was high (Pearson correlation coefficient = 0.99) indicating that snow depth reflects the SWE on the landform segments and that snow densities are relatively less influential.

Table 4.4 Pre-melt snow density in 2004 and 2005.

		Snow Density (kg m^{-3}) [#]			
	n	FS	BS	SH	F/P Value[¶]
2004 winter[$]	1	244	254	174	
2005 winter[†]	4	336^a (15%)	290^a (18%)	309^a (4%)	$0.9/4.3\times10^{-1}$

[#] *Values in the parenthesis are coefficient of variations (CV).* [$] *Values were measured on 09 March 2004.* † *Values were measured on 27 March 2005.* n – Number of samples for each landform segment. *Means with same letters are not significantly different at α = 0.05. Lowercase letters are used to compare snow density between columns.*[¶] *From ANOVA table. F, F statistics from ANOVA table; P, probability for F statistics from ANOVA table.*

Table 4.5 Pre-melt SWE in 2004 and 2005.

		SWE (mm) [†]			
	n	FS	BS	SH	F/P Value[¶]
2004 winter [#]	1	66	53	38	
2005 winter [$]	4	118^a (8%)	75^b (4%)	66^b (12%)	$47.1/8.6\times10^{-5}$

[#] *Values measured on 09 March 2004.* [$] *Values measured on 27 March 2005. † Values in parenthesis are coefficient of variations (CV).* n – Number of samples for each landform segment. *Means with same letters are not significantly different at α = 0.05. Lowercase letters are used to compare SWE between the columns.*[¶] *From ANOVA table. F, F statistics from ANOVA table; P, probability for F statistics from ANOVA table.*

During snow melt, the average snow density increased gradually (Figure 4.3) from 263 to 430 kg m^{-3}. This increase could be likely due to the storage of water within the snowpack during melt. Pomeroy and Gray (1995) reported that snow density during snowmelt varies due to storage and loss of melt water and densities commonly range between 350 kg m^{-3} and 500 kg m^{-3}. The temporal variation was similar for all the landform segments (Figure 4.3) except on 30 March and 1 April where the BS and the SH respectively showed comparatively higher snow density than that of other two landform segments. Spatial variability of snow density measurements and variation of water storage and loss from the snowpack could have been a factor in this observation. Snow density values measured during the spring melt in 2005 were not tested for statistical differences between the landform segments as only a single measurement for each landform segment was made each day during the melt.

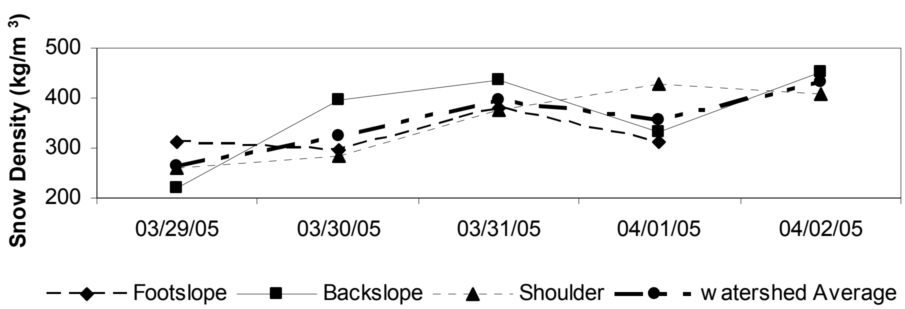

Figure 4.3 Variation of snow density measured during spring melt in 2005.

Since snow density was not measured during the melt in 2004 and was measured only at a subset of the sampling positions in 2005, a regression equation was developed using the 2005 data so that SWE could be estimated for all the snow depths for the melt period. Since Pomeroy and Gray (1995) identified snow depth, radiation during the melt, and cumulative temperature as the most important factors influencing snow density during melt, these parameters were used to develop a regression equation with the 2005 data (Equation 4.1).

$$\text{Snow Density}_{(i)} = 54 + 6.87\times CT_{(i)} + 14.9\times Rad_{(i)} + 2.78\times SD_{(i)} \qquad (4.1)$$

Where
Snow Density = snow density on i^{th} day (kg m^{-3})
CT = Cumulative of average daily temperature of i^{th} day (°C).
Rad = Solar radiation measurement for i^{th} day (MJ d^{-1})
i = 1, 2, 3…starting from 2 days before snowmelt runoff begins till complete disappearance of snow cover.
SD = Snow depth measured in cm for i^{th} day.

Temperature and radiation recorded at 30 minute intervals at the meteorological station near the site were used to estimate "CT" and "Rad" of Equation 4.1 for a given day. The "CT" was estimated as the summation of the daily average temperatures from two days before melting to the day concerned. The daily average temperature was estimated as the average of temperature values recorded at 30 minute interval for the day. The "Rad" was estimated as the summation of radiation values recorded at 30 minute intervals during the day.

The regression equation 4.1 had a high coefficient of determination (R^2= 0.96) but is valid only for the period starting from 2 days before melt to the date where the snow cover completely disappeared. The snowmelt period in 2005 was sunny and the daily solar radiation (Rad) was equal or above 10 MJ d^{-1} (data are not reported here). Equation 4.1 will not simulate snow density correctly during the days where solar radiation (Rad) is below 10 MJ d^{-1}. Figure 4.4 shows the estimated snow densities for the period of snowmelt in 2004 using equation 4.1. As solar radiation on 1 April 2004 was below 10 MJ d^{-1}, snow density for 1 April 2004 was estimated using the average of snow densities of the day before and of the day after. The estimated snow densities during the spring melt in 2004 for three landform segments were more or less similar and increased gradually from 345 kg m^{-3} to 508 kg m^{-3} (Figure 4.4). The range of snow density (345 - 508 kg m^{-3}) for the 2004 snow melt period was approximately equal to the range (350 - 500 kg m^{-3}) reported by Pomeroy and Gray (1995) for Canadian prairies.

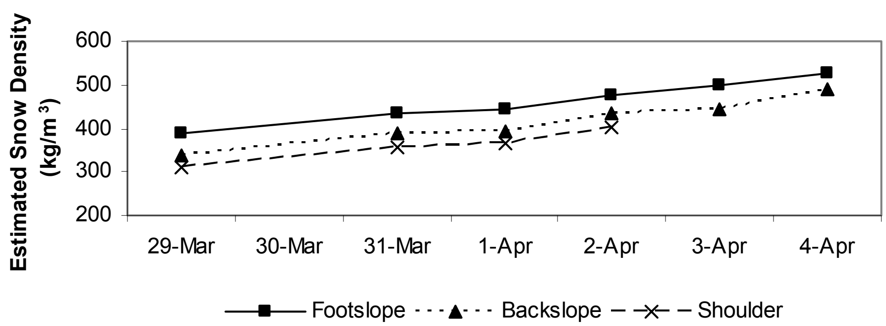

Figure 4.4 Estimated snow densities (using Equation 4.1) for the period of spring melt in 2004.

Estimated SWE in 2004 spring melt for each landform segment decreased with time (Figure 4.5) as melt water was lost from the snowpack. In 2005 spring melt, the estimated SWE for each landform segment, increased in value for 2 days following the start of melt (29 March 2005) and then decreased (Figure 4.5). The increase could be attributed to the errors in the density estimation using Equation 4.1. The SWE decrease in the later part of melt period occurred as melt water was lost from the snowpack.

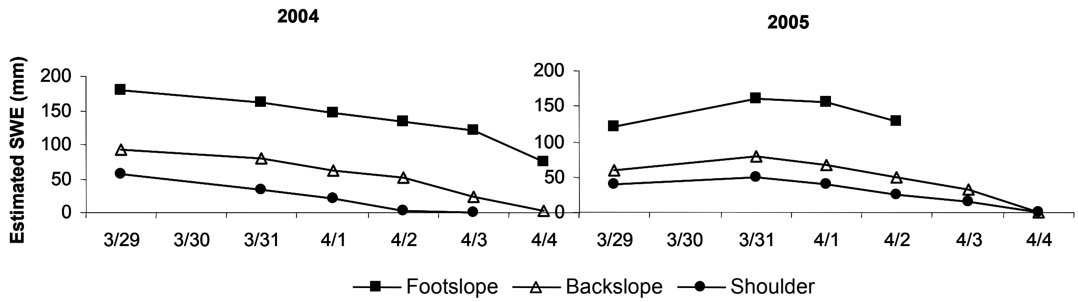

Figure 4.5 The SWE for the periods of snowmelt in 2004 and 2005.

4.6.4 Snowmelt runoff from closed plots

The entire watershed and the adjacent fields were under complete snow cover when the melting started and the weighted average of estimated SWE for the watershed were 83 mm (179 mm, 93 mm 57 mm, and 200 mm respectively in the FS, BS, SH, and the depression) and 58 mm (120 mm, 60 mm, 38 mm and 200 mm respectively in the FS, BS, SH and the depression) in 2004 and 2005, respectively. Snow began to melt on 29 March in both years. In 2004, snow melting began when the average air temperature was above 1 °C whereas in 2005, it started when the average temperature was above 3 °C. The number of days to initiate runoff from the day melting began varied highly with the plots, but the average number of days for the plots within a landform segment is presented here for comparison purposes (Table 4.6). There was no unique pattern with the number of days to initiate runoff among the landform segments. This variability could be explained by variability in snow melting, snow depth, structure of snow pack, snowmelt infiltration and micro topography within the plots in the landscape.

In this study, snowmelt runoff was measured from each plot until runoff ceased due to snow cover disappearance or until the plot was submerged due to flooding. The number of days of runoff from each plot also showed high variation. Some plots did not produce runoff everyday within the period between the initiation and cessation of runoff. However, the average number of days of runoff for the plots (Table 4.6) within each landscape position can be easily compared. The average number of days of runoff for each landform segment also varied (Table 4.6). The BS had a higher number of days of runoff than the SH (Table 4.6) for the closed plots in both winters and this could be attributed to the greater snow depth or SWE (Table 4.3 and 4.5) in the BS than in the SH. However, closed and open plots at the FS for both winters could not be compared due to flooding.

Table 4.6 Average number of days to initiate runoff and duration of runoff for landform segments

	Plot type	Winter	FS	BS	SH
#Average number of days to initiate runoff	Closed	2004	2	1	1
		2005	1	1	3
	Open	2004	2	1	
		2005	1	2	
Average duration (days)	Closed	2004	†	5	3
		2005	†	4	3
	Open	2004	†	5	
		2005	†	4	

FS, footslope; BS, backslope; SH, shoulder. # Average number of days to initiate runoff was estimated from the day snowmelt began. † Average runoff duration for the FS could not be estimated due to flooding.

Average daily snowmelt runoff was calculated as the average of the runoff volumes collected from each closed plot from all three landform segments for a given day. For the runoff plots which did not produce runoff between the initiation and cessation of runoff, and did not show any leak or damage, zero runoff was assumed in the calculation. The average of the daily snowmelt runoff from the closed plots (3.47×10^{-3} m^3 m^{-2} d^{-1}) in the 2004 snow melt period was significantly lower ($P = 5.1\times10^{-9}$) than that (12.7×10^{-3} m^3 m^{-2} d^{-1}) in 2005 spring melt.

In the 2004 snowmelt runoff period, the average daily snowmelt runoff from the closed plots, gradually increased (from 0.21×10^{-3} m^3 m^{-2} d^{-1} to 5.48×10^{-3} m^3 m^{-2} d^{-1}), and closely followed the pattern of daily average temperature (Figure 4.6). This could be attributed to (1) increasing rate of snow melting with the increasing air temperature, and/or (2) high infiltration into soil initially and reduction in infiltration with the progression of snowmelt.

In the 2005 snowmelt runoff period, the average daily snowmelt runoff values were much higher than in 2004 (Figure 4.6) and the duration of runoff period was shorter than in 2004 (Table 4.6). This could be likely due to lower infiltration rate in 2005 than in 2004. Initially the average daily snowmelt runoff in 2005 increased slightly with time and later decreased (Figure 4.6). This initial increase in runoff could be attributed to (1) increase in melt rate (started when daily average temperature was above 3 °C) and/or (2) reduction in infiltration rate with the progression of melting in 2005 melting season. The decrease in runoff in the later part of the runoff period in 2005 could be due to the limited snow on the ground.

In both snowmelt runoff periods, the average daily snowmelt runoff hydrograph (Figure 4.6) for closed plots increased within initial stage of snowmelt runoff period (i.e.

within first 3 days) and the later part of the hydrograph varied between the years. Therefore, the initial stage of the hydrograph appears to have been influenced by common factors in both periods.

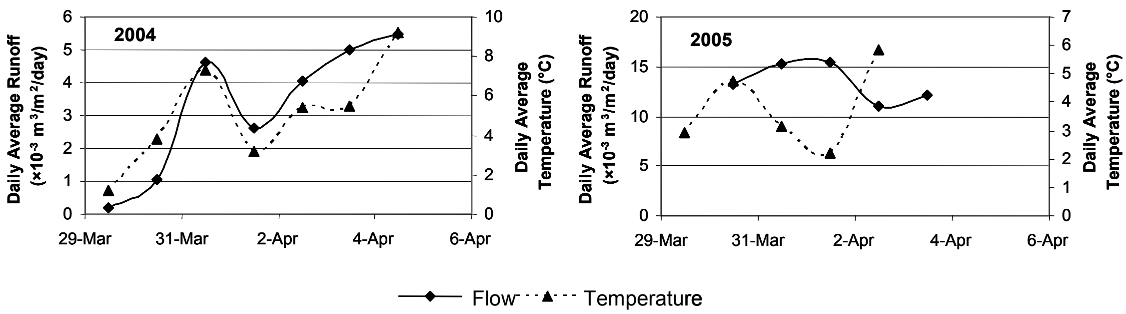

Figure 4.6 Daily average temperature and daily average runoff for the closed plots

Table 4.7 shows the average daily snowmelt runoff for each landform segment (i.e. the average of daily runoff values from each closed plot within the landform segment for the entire snow melt runoff period) and the average of total runoff (i.e. the average of total runoff from each plot within the landform segment for the entire snowmelt runoff period). For the runoff plots which did not produce runoff between the initiation and cessation of runoff, and did not show any leak or damage, zero runoff was assumed during average and total runoff calculation. Runoff data for the FS was incomplete due to flooding. Therefore, runoff value for the FS was not counted for comparison with other landform segments.

The average daily snowmelt runoff for the BS in 2004 and 2005 (3.98×10^{-3} and 14.6×10^{-3} m^3 m^{-2} d^{-1} respectively) was not significantly different from that of the SH in the 2004 and 2005 (2.95×10^{-3} and 11.9×10^{-3} m^3 m^{-2} d^{-1} respectively) (Table 4.7). Higher daily runoff was expected at the BS than at the SH because of higher SWE at the BS. However, high variability in the runoff within a landform segment (as shown by the high CV values in Table 4.7) could have masked any effect. For each landform segment, the average daily snowmelt runoff rate from closed plots in the 2005 spring melt period was higher than the values observed in the 2004 spring melt period (Table 4.7). This could be explained by the year to year variation in snow melting and snowmelt runoff conditions. Harms and Chanasyk (1998) also reported the high spatial variability in the timing and amount of hillslope snowmelt runoff between the plots at similar slope positions and between the slope positions along the same aspect.

Table 4.7 Average snowmelt runoff from the closed plots.

	Year	FS[#]	BS	SH	P Value[¶]
Average Daily Runoff (m^3 m^{-2} d^{-1})	2004	3.8×10^{-3} (119%)	4.0×10^{-3} aB (147%)	3.0×10^{-3} aB (85%)	0.59
	2005	-	14.6×10^{-3} aA (53%)	11.9×10^{-3} aA (80%)	0.43
P Value[¶]			3.3×10^{-5}	1.2×10^{-3}	
Average Total Runoff (m^3 m^{-2})	2004	-	19.8×10^{-3}	11.3×10^{-3}	
	2005	-	49.7×10^{-3}	33.5×10^{-3}	

[#] *Incomplete due to flooding. Values in parenthesis are coefficients of variation (CV). Means with same letters are not significantly different at* $\alpha = 0.05$. *Lower case letter are used to compare between the columns. Upper case letters are used to compare between the rows.* [¶] *From t-test.*

The average total snowmelt runoff for the BS in 2004 and 2005 (19.8×10^{-3} and 49.7×10^{-3} m^3 m^{-2} respectively) was higher than that of the SH in 2004 and 2005 (11.3×10^{-3} and 33.5×10^{-3} m^3 m^{-2} respectively) (Table 4.7) and this could be attributed to the higher SWE in the BS than in the SH in both years. However, these average total snowmelt runoff values could not be tested statistically because of the single value for each landform segment.

Based on the snowmelt runoff measurements using closed plots and SWE for the landform segments, the BS and the SH converted 21% and 20% of the SWE on average into snowmelt runoff in 2004, while in 2005, the BS and the SH converted 83% and 87% of SWE into runoff. The remaining portion of SWE could be attributed to the infiltration and or evaporation. Evaporation during the snowmelt runoff can be assumed as negligible because of the short snowmelt runoff duration (5 days) in this region. Therefore, the portion of SWE which was not converted to snowmelt runoff could be attributed to the infiltration. Irrespective of the year, both the BS and the SH produced approximately the same proportion of runoff from the available water (SWE before melting) in the winter.

4.6.5 Snowmelt runoff from open plots

The open plots started producing snowmelt runoff at least one day after melting began (Table 4.6). The number of open plots that produced snowmelt runoff varied with time within the snowmelt runoff period and was different from year to year. As the information on the closed and the open plots at the FS was incomplete due to flooding, and as the SH had no open plot, only the open and closed plots at the BS are compared in this paper. The average duration of runoff in the open plots was similar to that of the closed plots.

The average daily snowmelt runoff (12.2×10^{-3} m^3 d^{-1} and 19.1×10^{-3} m^3 d^{-1} respectively for 2004 and 2005) from the open plots were higher than the average daily snowmelt runoff for the closed plots (3.98×10^{-3} and 14.6×10^{-3} m^3 m^{-2} d^{-1} respectively for

2004 and 2005). The averages of total runoff values (59.4×10^{-3} m^3 and 65.4×10^{-3} m^3 respectively for 2004 and 2005) from the open plots were also higher than that from the closed plots at the BS (19.8×10^{-3} and 49.7×10^{-3} m^3 m^{-2} respectively in 2004 and 2005). This difference between open and the closed plots was likely due to the higher contributing areas for the open plots. Further, as we observed for closed plots, the average daily runoff and average total runoff for the open plots in 2005 were higher than that in 2004. This could be due to the year to year variation in snow melting, snowmelt infiltration, and contributing areas.

The instantaneous snowmelt runoff rate measured for both open and closed plots during the peak snowmelt of the day (late afternoon) in 2004 and 2005 varied largely between the days of a snowmelt runoff season and between the years. However, in both spring melt period, instantaneous runoff rates in open plots were higher than in closed plots for each day of the runoff season (data are not reported here), giving further evidence for the contribution of run-on in the open plots.

4.6.6 Water Balance

The water balance of the watershed, for the 2004 and 2005 snowmelt runoff periods is presented in this section. This water balance was estimated using measured runoff from the closed plots, along with the area for each landform segment.

The total volume of water input for the watershed (Table 4.8) was estimated using average pre-melt SWE for each landform segment and the respective areas of each segment of the watershed.

Table 4.8 Water input as snow (m^3) for the different landform segments.

	SWE (mm)		Area (m^2) #	Water input (m^3)		Proportion of water input	
	2004	2005		2004	2005	2004	2005
FS	179	120	849 (10%)	152	102	22%	21%
BS	93	60	1386 (17%)	129	83	19%	17%
SH	57	38	5606 (68%)	320	215	47%	45%
Depression	200	200	408 (5%)	82	82	12%	17%
Total			**8249**	**683**	**482**		

Values in parenthesis are proportion of landform segment area from total watershed area

In 2004, the total water input to the watershed was 683 m^3 while it was 482 m^3 in 2005 (Table 4.8). The major portion of water was held in the SH (47% and 45% respectively in 2004 and 2005) while the FS held the second highest water input of the watershed (22% and 21% respectively in 2004 and 2005).

At the end of the snowmelt runoff period, the total snowmelt runoff for the watershed (Table 4.9), estimated as the sum of snowmelt runoff from each landform segment, was 215 m^3 and 440 m^3 (31% and 91% of total water input) respectively in 2004 and 2005. For the BS and the SH, the total snowmelt runoff was estimated as the product of average of total snowmelt runoff (Table 4.7) from the 1 m^2 closed plots, and area of the landform segment. The water contributions to the runoff from the depression and the FS in 2005 (Table 4.9) were assumed to be equal to the water inputs (Table 4.8) as they were completely under water. In 2004, runoff from the FS was estimated as the sum of water contribution from the areas under water (16% of the area was under water) and the runoff from the rest of the FS areas. Even though the total snowmelt runoff from the FS in 2004 could not be measured due to flooding, runoff from the unflooded area of the FS was estimated using the average total runoff (m^3m^{-2}) of the BS (Table 4.7) adjusted to reflect the relative amounts of daily average runoff from the FS and the BS when flow could be measured from both positions (Table 4.7).

Table 4.9 Total snowmelt runoff (m^3) for different landform segments

	Runoff ($\times10^{-3}$ m^3 m^{-2})		Area (m^2)	Total Runoff (m^3)		Proportion of Runoff	
	2004	2005		2004	2005	2004	2005
Depression			408	82	82	38%	19%
FS			849	42	102	20%	23%
BS	19.8	49.7	1386	27	69	13%	16%
SH	11.3	33.5	5606	63	188	30%	43%
Total				**215**	**440**		

Of the three landform segments, the SH was the biggest contributor (30% and 43% of total runoff respectively in 2004 and 2005) to the total snowmelt runoff of the watershed in both years (Table 4.9) and this was due to the larger SH area of the watershed. The BS contributed the least (13% and 16% of total snowmelt runoff respectively in 2004 and 2005). The FS, BS and SH, converted 27, 21 and 20 percent respectively of its respective water inputs (Table 4.8) to runoff in 2004 and 100, 83 and 87 percent in 2005.

The evaporation losses from this watershed during the snowmelt period were likely a minor component of the water balance equation because of the short snowmelt runoff period (4-5 days) and therefore, were assumed to be zero in this study. Bengtsson (1980) also proposed that evaporation from the snow pack is a minor component of the mass balance equation during the snowmelt. Therefore, snowmelt infiltration over the entire watershed was estimated as the difference between total water input to the watershed (Table 4.8) and total runoff (Table 4.9). The total infiltration over the watershed was 468 m^3 and 42 m^3 (69% and 9% of total water input) respectively for 2004 and 2005. On a frozen silt loam soil in northern Oregon, Zuzel et al. (1982) estimated infiltration to be about 41-91% of snowmelt water. In a similar soil in Fairbanks, Alaska, Kane and Stein (1987) estimated infiltration to be about 53-75% of the snowmelt water.

In the spring 2004, high infiltration proportions could likely be due to the lower soil moisture content in the fall 2003 than the fall soil moisture content in 2004 (Priyashantha et al., 2007). High fall moisture condition before soil was frozen in fall 2004 could have limited infiltration during the snowmelt period in 2005. Moncrief et al. (2005) also reported that in years, when soil water contents at freezing were high, infiltration of the snowmelt water decreased to between 24 and 47%. Another significant contribution could have resulted from crack and macro-pore formation in the soil during manure injection in fall 2003 which would have increased infiltration in the following spring (2004).

In 2004, the maximum volume of water accumulated in the depression was 120 m^3 whereas in 2005, it was 424 m^3. These volumes were estimated using measured water levels in the center of the depression using ultrasonic depth sensor (SR-50). The difference between total runoff and water accumulated in the depression (i.e. (215 - 120) m^3 and (440 – 424) m^3 respectively in 2004 and 2005) at the end of the melt period, can be accounted for losses through evaporation and focused infiltration in the depression during the snowmelt event. As mentioned in the previous section, if evaporation from the depression is assumed to be negligible during this short melt event, the infiltration under the depression is equal to 95 m^3 and 16 m^3 respectively in 2004 and 2005.

The surface area of the depression at maximum water depth (544 m^2 and 1256 m^2 respectively for 2004 and 2005 snowmelt runoff periods) and the number of days to reach maximum water level in the depression (7 and 6 days respectively in 2004 and 2005) were used to estimate the infiltration rate under the water filled depression. Even though the surface area of the depression varied with the time during the snowmelt runoff season, surface area of the depression at maximum water depth was used because of the short melt period in both years. The estimated snowmelt infiltration rates under the depression for the snowmelt runoff period were 1.04 mm hr^{-1} and 0.09 mm hr^{-1} respectively in 2004 and 2005. The depression focused infiltration was higher in 2004 than in 2005, as was observed for infiltration throughout the watershed.

4.7 Conclusions

The average snow depth in the watershed at onset of melting did not vary between two winters. However, snow depth varied between the landform segments. In 2004, snow depth had a distribution pattern of SH < BS < FS while in 2005, the distribution pattern was SH = BS < FS. The pre-melt snow density did not show any specific pattern of variation with the landform segments in either winter. During melting, the average snow density increased as melting progressed. The pre-melt SWE increased in the down slope direction having the lowest in the SH and BS and the highest in the FS in 2005. The BS and the SH had similar SWE in 2005 (the only year when SWE was measured for different landform segments).

Daily snowmelt runoff from 1 m^2 plots also showed temporal and spatial variation during the snow melt period and also varied between the years. The average of the daily snowmelt runoff from the closed plots (3.47×10^{-3} m^3 m^{-2} d^{-1}) in the 2004 snow melt period was lower than that (12.7×10^{-3} m^3 m^{-2} d^{-1}) in 2005 spring melt. The average daily snowmelt runoff and the average of total snowmelt runoff from 1 m^2 plots did not vary between the SH and the BS. Further, irrespective of the year, the closed plots at both BS and the SH produced approximately the same proportion of runoff on average from the available water (SWE before melting) in the winter. However, in both snowmelt periods, the average runoff (combination of runoff and run-on) at the BS estimated using open plots were greater than the average runoff estimated using closed plots because of the larger contributing areas for the open plots. Further, as we observed for closed plots, the average daily runoff and average total runoff from open plots at the BS varied with the year and 2005 had higher runoff than in 2004.

Total snowmelt runoff to the depression varied with the year. The total runoff from the entire watershed was 214.6 m^3 and 440.2 m^3 (31% and 91% of total water input) respectively for 2004 and 2005. The total infiltration over the watershed was 468 m^3 and 42 m^3 (69% and 9% of total water input) respectively for 2004 and 2005. Dry fall soil condition and cracks and macro-pores created during manure injection in the fall were likely the reason for higher infiltration in 2004 than in 2005.

Of the three landform segments, the SH was the biggest runoff contributor (30% and 43% of total runoff respectively in 2004 and 2005) to the depression in both years. The BS contributed the lowest (13% and 16% of total snowmelt runoff respectively in 2004 and 2005). The FS, BS and SH, converted 27, 21 and 20 percent respectively of its respective water inputs to runoff in 2004 and 100, 83 and 87 percent in 2005. The estimated snowmelt infiltration rates under the water filled depression were 1.04 mm hr^{-1} and 0.09 mm hr^{-1} respectively in 2004 and 2005.

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CHAPTER 05

Impact of slope position on snowmelt runoff water quality in a small closed-catchment in an undulating landscape.

5.1 Abstract

The quality of snowmelt runoff in a small closed agricultural drainage basin, where hog manure had been fall injected was studied. Measurements were made in 2004 and in 2005 to (1) investigate the quality of snowmelt runoff, (2) to investigate the spatial association between quality of snowmelt runoff and landform segments, and (3) to understand the factors controlling snowmelt runoff water quality. Concentrations of total phosphorus (TP), total dissolved phosphorus (TDP), nitrate-nitrogen (NO_3-N), and sediment were measured in daily snowmelt runoff samples collected from open and closed plots at the shoulder (SH), backslope (BS) and the footslope (FS) landform segments. Nutrient and sediment loads were estimated using runoff volumes with the respective concentrations.

Snowmelt runoff water quality measured using closed plots varied within and between the years. Hog manure injection below the runoff-soil interactive layer did not appear to influence snowmelt runoff water quality. More than 85% of TP was in the dissolved form (TDP). The total mass of nutrients and sediments in snowmelt runoff was greater in 2005 than in 2004 because of the higher runoff in 2005. On average, snow contained the equivalent of 10% and 27% of TP in snowmelt runoff in 2004 and 2005 and the equivalent of 7% of snowmelt runoff NO_3-N in 2004. Most nutrients and sediments were from the land surface due to interaction between snowmelt runoff and the land surface. Analysis revealed that fall soil nutrient concentrations were not a dominant factor controlling the nutrients in the snowmelt runoff at this site. However, snowmelt runoff volume controlled snowmelt runoff water quality. Snowmelt runoff water quality did not vary between the landform segments. However, as a result of the areal dominance of the SH segment in this landscape most of the nutrients in accumulated runoff originated in the SH. Snowmelt run-on influenced runoff quality and quantity in 2004 but not in 2005
.

Key words: Snowmelt runoff, Water quality, Total phosphorus, Nitrate, Sediment

5.2 Introduction

Hog manure application as a crop fertilizer, is an environmentally sustainable solution to a waste disposal problem, but could pose a risk to surface water quality. Nutrients, applied in excess of crop requirements, can accumulate in the soil and be transported with runoff leading to eutrophication of surface waters. The effect of land applied manure on the quality of runoff water has been studied extensively (Edwards and Daniel, 1994; Sharpley et al., 1994; Catt et al.,1998; Hansen et al., 2000; Gburek et al., 2002; Enright and Madramootoo, 2004). These studies have mostly focused on the quality of runoff waters generated through rainfall.

However, there is limited information on nutrient losses through snowmelt runoff. In west-central Minnesota, Burwell et al. (1975) reported snowmelt to be the most critical runoff period in terms of soluble nutrient losses. Chanasyk and Woytowich (1986) reported that snowmelt, especially when the soil is still frozen, has been identified as the major cause of runoff and soil erosion in a high latitude landscape. Ginting et al. (1998) reported that loss of water soluble contaminants in snowmelt runoff can be considerable even though snowmelt runoff is not as erosive as rainfall runoff. Ghidey et al. (1999) reported lower ortho-P (i.e. dominant form of total dissolved P) concentration in spring snowmelt than in runoff in summer months and this was attributed to the dilution from the snowpack and to the colder temperatures which slow down mineralization of P preventing the release of P to surface waters. Hansen et al. (2000) reported that snowmelt runoff is not considered to cause substantial inter-rill erosion because snow normally melts gradually and soil detachment is limited when soil is frozen. In a study where hog manure injection into the soil at two rates (a low rate of 220 kg N ha^{-1} and 62 kg P ha^{-1} and a high rate of 307 kg N ha^{-1} and 67 kg P ha^{-1}), was compared to an inorganically fertilized control at a site in Saskatchewan, Canada, Elliott and Maulé (2001) reported that concentrations of TP, Ortho-P and NH_3 in snowmelt runoff from the basin receiving the high rate of hog manure increased relative to the background measurements and the control basin. In the same study, they reported elevated NH_3 concentration in the snowmelt runoff from the basin receiving the low rate of hog manure.

Ginting et al. (1998) reported that particulate P loss with snowmelt runoff was higher from no-manure ridge-till plots than manure ridge-till plots which had a one time application of 164 kg P ha^{-1} from solid beef manure. This was attributed to the higher sediment loss in snowmelt runoff from no manure ridge till plots than that from manure ridge-till plots. For the same experiment, Ginting et al. (1998) reported similar dissolved molybdate reactive P loss in snowmelt runoff from manured and control plots.

Because of the limited information, nutrient losses during the snowmelt runoff period are not well understood. In the Canadian prairies, there is lack of information on the water quality of snowmelt runoff from agricultural lands, where hog manure had been applied, to topographic depressions or similar topographic structures (e.g. lakes and wetlands). This is of growing importance since the hog industry in the Canadian prairies is experiencing rapid growth and fall application of hog manure to agricultural lands is increasing (Pastl et al., 1999). Increased nutrient concentrations in snowmelt runoff could lead to eutrophication of receiving waters such as wetlands and lakes (Chambers et al., 2001) and ground water quality impairment (Hayashi et al., 1998).

In the Canadian prairie landscape, closed topographic depressions are common features which collect runoff water from the surrounding areas during snowmelt and heavy rainfall periods. These depressions have important functions with respect to surface water storage, surface and ground water quality, ground water recharge, subsurface contaminant movement and ecology (Hayashi et al., 2003). Granger and Gray (1990) reported that the shallow snowcover in the semi-arid region of the Canadian prairies generates 80% or more of the annual surface runoff, although only approximately one-third of the annual precipitation in the region occurs as snowfall. Therefore, snowmelt runoff is the major water input to the depressions, lakes and wetlands in the Canadian prairies and provides a valuable source of water for domestic, livestock, irrigation purposes and for wildlife habitats. Therefore, studies on the quality of snowmelt runoff from the surrounding agricultural lands receiving hog manure in the fall are important for the proper implementation of water quality management practices.

This study investigates the quality of snowmelt runoff generated in an agricultural closed drainage basin in the Canadian prairies. In order to implement control measures that reduce or prevent the nutrients from contributing to the surface waters through snowmelt runoff, we must understand the effect of landscape position upon the quality of snowmelt runoff. Therefore, the objectives of this study are: (1) to investigate the quality of snowmelt runoff (total phosphorus (TP), total dissolved phosphorus (TDP), nitrate-nitrogen (NO_3-N) and sediment) from agricultural land where hog manure had been injected; (2) to investigate the spatial association between quality of snowmelt runoff and landform segments; and (3) to understand the importance of snowmelt runoff (transport factor) and fall soil residual nutrients (source factor) on snowmelt runoff water quality. Greater understanding of factors that control the snowmelt runoff water quality in Canadian prairies and the presentation of snowmelt runoff water quality for different landform segments with injected hog manure in the fall will be significant contributions of this study to the existing knowledge gaps.

5.3 Literature Review

5.3.1 Nutrient losses through runoff

Nutrient losses through rainfall runoff have been studied extensively. The major mechanism through which P is lost from agricultural land is surface runoff carrying P in both soluble and particulate forms (Sharpley et al., 1994). For example, Catt et al. (1998), in a British study reported that P losses occur mainly in particulate forms and are consequently greater in surface runoff than in tile drainage flow from experimental plots.

Runoff volume, sediment loss, forms and concentration of soil P, and depth of mixing of soil and water are some of the factors affecting the loss of P through runoff (Sharpley et al., 1994). Edward et al. (2000) reported that the magnitude of P loss was related to the temporal proximity of preceding rainfall in a simulated rainfall study. Other factors such as precipitation and soil surface characteristics that vary temporally and spatially are also important in determining P loss (Gburek et al., 2002). McDowell and Sharpley (2002) reported that antecedent soil moisture influenced P transport. Enright and Madramootoo (2004) reported that soil test P and percent P saturation were inadequate indicators for the potential of P pollution. The concentration of P in runoff is further influenced by the timing of precipitation and vegetative cover because precipitation provides the major source of energy for soil erosion, transport and soil water interaction.

Finer soil particles could carry a higher amount of adsorbed nutrients than the bulk soil (Sharpley and Smith, 1991). Sharpley et al. (1992) reported that particulate P is the largest fraction of P in runoff from row-crop production systems because of large losses of sediment from the row-crop production system. Wall et al. (1996) showed that the TP losses decreased with decreasing loss of sediments, which have more readily adsorbed P. In the coastal plain of Maryland, Jordan et al. (1997) showed a correlation between P and sediment concentration in runoff, but reported that the correlation relationship differed among the seventeen watersheds that were studied. Westermann et al. (2001) concluded that TP in runoff was not related to the soil P but was linearly related to sediment concentration, from a study in southern Idaho. Enright and Madramootoo (2004) observed that the majority of the annual P losses from two field sites located in the Pike River watershed of southwestern Quebec occurred with surface runoff.

Agricultural practices that affect surface runoff and sediment load, also govern nutrient losses with runoff as nutrients are transported both with sediment and in solution. Baker (1985) reported that conservation tillage controls sediment and sediment-associated P losses. However, some studies reported that nutrient concentration in surface runoff increased due to conservation tillage (Barisas et al., 1978; Ghidey et al., 1999). Since the fertilizer was surface applied and not incorporated into the soil in the conservation tillage systems, nutrient losses could be high in surface runoff especially for the runoff events that occur within a few weeks of fertilizer application. Since P can accumulate in the surface layer of the soil due to a lack of soil inversion and nutrient leaching from the surface residue (McDowell and McGregor, 1984), Ginting et al. (1998) suggested that the effect of conservation tillage on dissolved P in the surface runoff should be considered.

The nutrient concentration in surface runoff can also be influenced by the rate of fertilizer (or manure) application, incorporation, and timing of the runoff event related to fertilizer application. Klausner et al. (1974) showed that excessive fertilizer application and fertilizer application prior to the wet season increased the susceptibility of nutrient losses to surface runoff. Johnson and Moldenhauer (1979) reported that N loss to surface runoff was greater immediately after surface application of fertilizer. Several studies reported that nutrient loss to surface runoff was small compared to the amount of fertilizer applied and most of the losses occurred with the sediment in the runoff (Blevins et al., 1990; Owens and Edwards, 1993).

Degree of wetness (i.e dry or wet) of the year also has an impact on the amount of nutrient losses from a watershed. Gaynor and Findlay (1995) reported that dry and wet conditions have little effect on ortho-P losses to surface runoff. Catt et al. (1998)

reported a three fold increase in TP losses in surface runoff between a dry and a wet year. Ghidey et al. (1999) observed that NO_3^- loss to surface runoff was highly related to runoff volume for the rainfall events that occurred soon after the fertilizer application.

As we illustrated here, factors affecting nutrient losses through surface runoff have been studied extensively. However, nutrient losses through the runoff at different landform segments have not been studied.

5.3.2 Nutrient losses through snowmelt runoff

Extensive research work has been done to understand the nutrient loss through runoff caused by rainfall. However, there is limited information on nutrient losses through the snowmelt runoff. Hence, nutrient losses during snowmelt runoff period are not understood as well as the nutrient losses due to rainfall.

For a site in eastern South Dakota, Harms et al. (1974) reported that the major portion of the annual nutrient load (P and N) came from snowmelt runoff and a large percentage was soluble. In west-central Minnesota, Burwell et al. (1975) reported that snowmelt was the most critical runoff period for soluble nutrient losses and much of the annual soluble nutrient losses occurred through snowmelt runoff. Ghidey et al. (1999) reported low ortho-P concentration in the spring snowmelt and attributed this to the dilution from the snowpack and colder temperatures which slows down mineralization of P.

Timmons et al. (1970) reported that the drying and freezing of plant tissue could increase the amount of N and P in leachate. The biomass on the ground goes through a sequence of freezing and thawing during the winter and spring months and that causes ruptured cells and result in release of nutrients during the next rainfall or snowmelt runoff event (Ginting et al., 1998).

Nutrient losses from native prairie represent natural levels and can be used to compare the effects of different land use on nutrient loads and surface runoff. Timmons and Holt (1977) reported that 63-88% of the annual nutrient loads from native prairies (west-central Minnesota) came from snowmelt runoff. Average annual total N and TP losses were 0.8 and 0.1 kg/ha respectively. Timmons and Holt (1977) further reported that nutrients transported by snowmelt runoff from native prairies originated from a combination of the leaching from prairie vegetation and decomposing surface mulch, and from the precipitation itself. Soil nutrients did not contribute to snowmelt runoff because of a thin ice layer that formed at the soil surface, separating snowmelt runoff from the soil.

Chanasyk and Woytowich (1986) reported that snowmelt and rains on snow especially when the soil is frozen have been identified as main causes of runoff and soil erosion in high latitude landscapes. Ginting et al. (1998) reported that loss of water soluble nutrients in snowmelt runoff can be substantial even though snowmelt runoff is not as erosive as rainfall runoff. In general, snowmelt runoff does not cause substantial inter-rill erosion, relative to rainfall runoff, because snow normally melts gradually and soil detachment is limited when soil is frozen (Hansen et al., 2000).

Khaleel et al. (1980) reported that nutrient losses were considerably higher when manure was applied on land subject to snowmelt runoff. Thus higher concentrations and loads can be expected from application of manure in spring and winter months than in summer and fall. Khaleel et al. (1980) further reported that application of manure in solid form and incorporated into the soil results in lower runoff nutrient losses. Ginting et al. (1998) reported that particulate P loss with snowmelt runoff from no manure ridge till was higher than in runoff from manure ridge till plots which had one time application of 164 kg P ha^{-1} from solid beef. This observation was attributed to the greater sediment loss in snowmelt runoff from no-manure ridge till system than that from manure ridge till system. For the same experiment, Ginting et al. (1998) reported similar dissolved molybdate reactive P loss in snowmelt runoff from manured and no-manured plots. In a study where hog manure injected into the soil at a low rate of 220 kg N ha^{-1} and 62 kg P ha^{-1}, and a high rate of 307 kg N ha^{-1} and 67 kg P ha^{-1}, was compared to an inorganically fertilized control at a site in Saskatchewan, Canada, Elliott and Maulé (2001) reported that concentrations of TP, ortho-P and NH_3 in snowmelt runoff from the basin receiving the high rate of hog manure increased relative to the background measurements and the control basin. They further reported elevated NH_3 concentration in the snowmelt runoff from the basin receiving the low rate of hog manure.

The influence of fall soil nutrients and landscape position on the quality of snowmelt runoff water has not been studied in the Canadian prairies. This information is vital for the proper implementation of management practices to control the quality of snowmelt runoff waters.

5.4 Site Characteristics

The study site, chosen within one farm field as being representative of the local landscape, is a small closed drainage basin of 8249 m^2 with an average slope of 2.7%. The site is located near the town of Elstow (52° 02' N, 106° 06' W), 55 km east of the city of Saskatoon, Saskatchewan, Canada. During the spring melt season, snowmelt runoff generated within the watershed accumulates in a central depression (408 m^2) from which it completely infiltrates over the following several weeks. The surrounding landscape is undulating with local small hilltops and depressions consisting of fine textured lacustrine material over till. Ephemeral puddles, formed in these depressions, can play an important role in the hydrology and ecology of the area, by storing runoff water, recharging soil moisture and shallow ground water (Hayashi et al., 2003). The soil is classified as an Orthic Dark Brown Chernozem of the Elstow Association consisting of medium to moderately fine textured, moderately calcareous, clayey glacio-lacustrine deposits (Acton and Ellis, 1978). Texture of the upper 15 cm of soil is clay loam to silty clay.

The study site, including surrounding fields, received agitated hog manure at the rate of 56.2 m^3 ha^{-1} (approximately 125 kg N ha^{-1} and 36 kg P ha^{-1}) in the falls of 2001 and 2003. The manure was supplied by a local hog barn (about 2 km south east of the site) operated through the Prairie Swine Centre and the application rate was based on a common rate used in the province. Manure application in the fall 2003 was done on 2 October 2003. Manure was applied in east to west direction by a commercial operator.

Knife openers injected the manure to a depth of 10-12 cm and a compaction wheel followed to close the injection slots. Manure samples were collected throughout the application and analyzed for nutrient concentrations. The average N content (2.2 g N kg^{-1}) in the liquid hog manure was approximately 3.5 times higher than the P content (0.7 g P kg^{-1}). Nearly 61 % of the total N (1.4 g N kg^{-1}) in the hog manure was in the available form (mostly as NH_4^+-N) while 20 % of TP (0.1 g P kg^{-1}) was in the available form. Daniel et al. (1994) and Schoenau et al. (2000) also reported similar results with liquid hog manure. In this study, we assumed that N and P addition through hog manure to each landform segments was similar.

Reduced tillage practices were used on this field. With exception of manure application, the seeding operation was the only disturbance in the reduced tillage system in use at the study site. An air seeder with a sweep opener was used to seed and the soil was subsequently harrowed and packed. Previous to the study, the field had been under cereal crop production (mainly cereal grains such as wheat and oilseeds such as canola). Canary seed (*Phalaris canariensis*) and wheat (*Triticum aestivum* L.) were grown in 2003 and 2004 respectively. Crops had been harvested from the site at the time of manure application and fall soil sampling. Average stubble height was about 15 cm in both years. According to visual observations, there was more stubble on the FS than on the BS and the SH. Crops had been planted in rows running in east-west direction in both years.

A meteorological station, installed 0.5 km east of the site, recorded temperature and rainfall data from 2002 to summer 2005. For comparison purposes climatic normals

(1971-2000) from the town of Viscount (51° 57’ N, 105° 37’ W) about 30 km to the east of the site, were used (Environment Canada, 2005). Since monthly air temperatures are below 0°C from November through March, a hydrological year is defined starting on November 1 and ending on October 31 (Hayashi et al., 1998). A hydrological year consists of a winter (November to March), a spring (April and May), a summer (June to August) and a fall (September and October). The mean annual precipitation at Viscount is 412 mm, of which 84 mm (20% of mean annual precipitation) occurs in the winter, mostly as snow, 184 mm during the three summer months (June, July and August) and 63 mm during the fall (1971-2000 climate normal).

This chapter presents the results of the snowmelt runoff water analysis for TP, TDP, NO_3-N and sediment of snowmelt runoff sampled at three different landform segments during 2004 and 2005 spring melt periods. Spring snowmelt was defined as the period of sustained melt when the snowpack melts at the end of the winter. The study period was characterized by a relatively dry summer and fall in 2003 (143 mm and 45 mm respectively) and a normal summer (183 mm) in 2004 followed by a dry fall (32 mm). Summer and fall in 2003 were warmer (17.4°C and 7.8°C respectively) than normal temperatures, whereas summer and fall 2004 were cooler (14.2°C and 6.4°C respectively) than normal.

5.5 Materials and Methods

The site was divided into landform segments (i.e. SH, BS, FS and depression) using a digital elevation model (DEM) derived from topographic survey data for the site. The SH (5606 m^2), the BS (1386 m^2) and the FS (849 m^2) were selected for this study as they were the areas upslope of the depression and that contributed flow to the depression. Six sampling transects were established, radiating outwards from the central depression and each running from the FS to the SH in the directions of NE, E, SE, SW, W, and NW. Three sample locations per transect were picked such that each landform segment was represented. We did not sample randomly within landform segments to minimize the disturbance to the snowcover during the winter measurements and to facilitate easy access during the spring sampling.

Nutrient availability in fall 2003 and 2004 in the top 5 cm of the soil at the sampling locations is reported in chapter 3. Available soil P concentrations for the FS, the BS and the SH, respectively were 7, 3 and 12 mg P kg^{-1} in the fall 2003 (after manure application [ama]), while in fall 2004, they were equal to 14, 10 and 19 mg P kg^{-1} of soil (Table 3.5 in chapter 3). The 2003 soil NO_3^- concentrations (ama) in the FS, BS and the SH were 72, 68, and 64 mg NO_3^- kg^{-1} respectively and for fall 2004 were 83, 38, and 18 mg NO_3^- kg^{-1} respectively (Table 3.6 in chapter 3). The 2003 soil NH_4^+ concentrations (ama) in the FS, the BS and the SH were 247, 147, and 246 mg NH_4^+ kg^{-1} and for fall 2004 were 9, 6, and 4 mg NH_4^+ kg^{-1} of soil respectively (Table 3.7 in chapter 3).

Hillslope runoff was measured using 1 m^2 plots installed at each sample location in the fall 2003 and fall 2004 before the soil was frozen. Each runoff plot in the BS and the FS consisted of two 1 m^2 plots placed one below the other and in line with down slope direction (Figure 5.1). The upslope runoff plot had only three sides and was open to the upslope side to catch run-on (i.e. runoff water from upslope areas of the sampling location) to the sampling location and this plot was referred to as “open plot” in this study. The downslope runoff plot was a closed on all four sides and was referred to as “closed plot” in this study. All runoff plots at the SH were closed plots. Open plots were not established at the SH as it was assumed that there was no run-on to these sampling locations as they were at the edge of the watershed. In total there were 18 closed plots and 12 open plots in the watershed. The runoff plots were hydrologically separated by metal plates extending 10 cm into the ground and 10 cm above the ground. On the open plots, the upslope plate was omitted to catch runoff coming directly from the upslope areas. Runoff from a runoff plot was routed through a pipe into a collection bag placed in a hole below the ground surface. The connections between the pipe and the metal plates were sealed using glue. Each hole was covered with a piece of polyethylene sheet during the winter to avoid snow falling into, and subsequently melting inside, the hole. Snow and the polyethylene sheet above each hole were removed before melting began. Although runoff plots in the FS position were placed above the 2003 high water mark, they were inundated with water midway through spring runoff in 2004 and were inundated on the first day of runoff in 2005. Some BS plots were inundated toward the end of spring runoff in 2005.

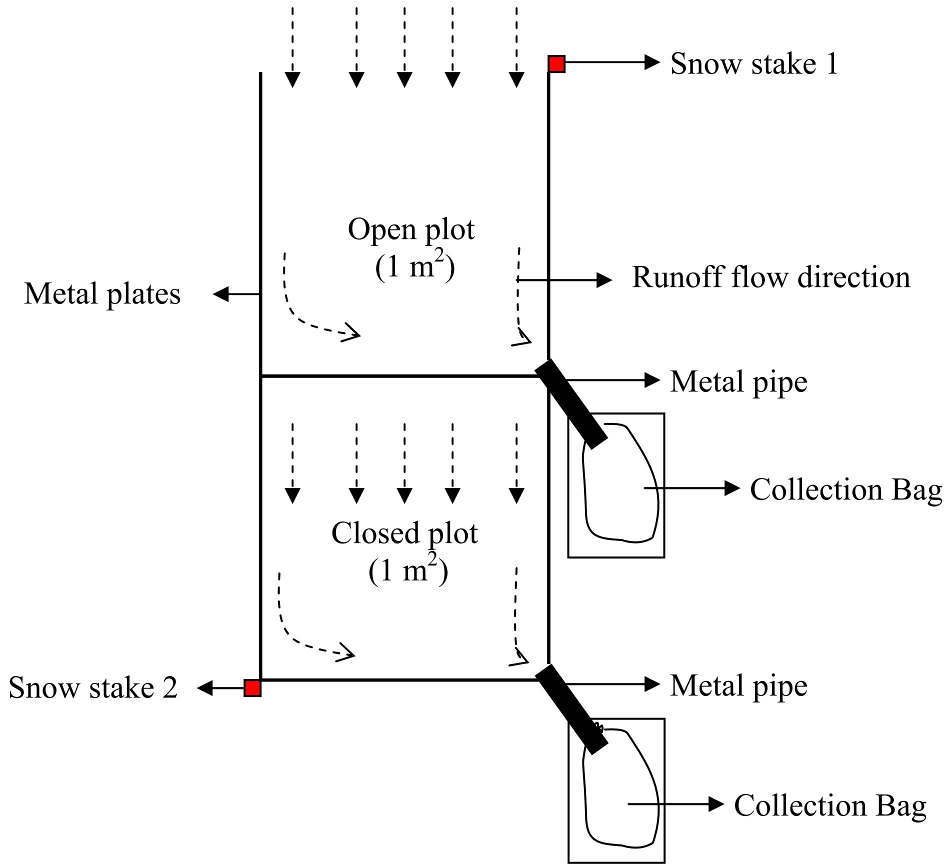

Figure 5.1 A schematic diagram of runoff plots with a closed plot and an open plot placed in a down slope direction at a sampling location.

The pre-melt snow depth survey was conducted on 09, 27 March 2004, and 27 March 2005 using snow stakes installed at the plot locations. Snow samples were collected during the snow surveys on 09 March 2004, and 27 March 2005. On 09 March 2004, one snow sample from each landform segment along the north-south transect was collected. On 27 March 2005, four snow samples were collected from each landform along south, north, west and east transects. These snow samples were transferred to clean polyethylene bags and stored in a cooler. The samples were transported to Saskatoon and stored overnight at 4°C. The SWE of pre-melt snow samples was estimated by measuring the volume of each snow sample upon melting. Snow density was determined for the samples using their weights and the volumes. All the 2004 samples were bulked together while the 2005 samples were bulked based on landform segments. Bulk samples were immediately submitted for nutrient analysis (ammonia nitrogen (NH_3-N), nitrate and nitrite nitrogen (NO_2 + NO_3-N), ortho-P, and TP). Nutrient analysis was performed by Environment Canada's Regional Water Quality Laboratory in Saskatoon using standard colourimetric methods. Total P and NH_3 were determined on unfiltered samples but aliquots for nitrite-nitrate (NO_2-NO_3) and ortho-P were filtered through a Whatman glass microfibre filter that had been baked for 4 h at 525 °C. Phosphorus was measured as ortho-P by reduction using stannous chloride (Environment Canada, 1979a). For the determination of TP, the aliquot was treated with a sulphuric acid - persulphate mixture to release organically bound phosphates and hydrolyze polyphosphates to ortho-P prior to reduction (Environment Canada, 1979b). The automated cadmium reduction method described by Clesceri et al. (1989) was used to determine NO_2-NO_3. Sulphuric acid was used to stabilize the final aliquot prior to ammonia determination by reaction with hypochlorite and alkaline phenol (Skougstad et al., 1979).

During the spring snowmelt in 2004 and 2005, the bags with runoff water were detached from the pipes daily and the volume of runoff water accumulated in each collection bag was measured. At the same time, sub samples were taken from these bags for nutrient and sediment analysis. Time of sampling and runoff volume measurement varied with the day depending on the field and weather conditions. However, most of these sampling and measurements were taken in the late afternoon and early evening (e.g. 3 pm-7 pm) of the day. A new bag was attached to each pipe once the collection bag with runoff water was detached from the pipe.

The water samples were shipped in a cooler to the lab in Saskatoon. These samples were stored in dark cooler at 4 °C until they were analyzed for nutrients. Measured parameters included sediment, NO_3-N, TDP and TP. Total P and TDP were analyzed in Environment Canada's water quality laboratory. Analysis for TP was described above and that for TDP differed only in that the sample was filtered to remove particles greater than 1.2 μm in diameter. Only selected runoff samples were analyzed for TDP in 2004 but in 2005 all samples were analyzed. The NO_3-N was analyzed using ORION (model 93-07) NO_3^- probe (Accuracy, 97%; Sensitivity, 3 mV per 1 ppm of NO_3-N) at the Department of Agricultural and Bioresources Engineering, University of Saskatchewan, Saskatoon. Results of the NO_3-N analysis in 2005 are not reported as values were abnormally high due to unexplainable reasons. The sediment concentration was determined by evaporating 200 mL of sub sample by oven drying at 104 °C and weighing the remaining solids.

The hydrologic conditions in the basin during 2004 and 2005 have been discussed in detail by Priyashantha et al. (2007b) and chapter 4. The entire watershed was under complete snow cover when melting started and the weighted average of snow water equivalents (SWE) for the watershed were 83 mm (179, 93, 57 and 200 mm respectively for the FS, BS, SH and the depression) and 58 mm (120, 60, 38 and 200 mm respectively for the FS, BS, SH and the depression) in 2004 and 2005 respectively. The total runoff in 2004 was 215 m^3 out of which the SH, BS, FS and the depression contributed 30%, 13%, 20% and 38% respectively. The total runoff in 2005 was 440 m^3 out of which the SH, BS, FS and the depression contributed 43%, 16%, 23% and 19% respectively. In 2004, a much greater proportion of snowmelt infiltrated than in 2005.

Flow-weighted (FW) mean concentrations were calculated for each individual plot by weighting the daily concentration data according to the proportion of total flow. Average concentrations of the water quality parameters for each plot type were simply estimated by averaging all the values (concentration and FW concentration separately) measured using respective plots types during the snowmelt period. The daily average load rates (mg m^{-2} d^{-1} for closed plots and mg d^{-1} for open plots) of sediment, TP, TDP, and NO_3-N for each plot type (open and closed plots) were calculated by averaging the products of the daily flow volume (L m^{-2} d^{-1} for closed plots and L d^{-1} for open plots) and the corresponding daily concentrations (mg L^{-1}) for all the plots. Water quality parameters for each landform segments were estimated using the above procedures after grouping data into landform segments. Averages of water quality parameters for the snowmelt runoff period were presented using averages of the all closed plots.

The values of sediments, TP, TDP, and NO_3-N for each landform segment were initially grouped into box plots, which allow both the median and dispersion of values to be visually assessed. The results were tested for normal distribution with Shapiro-Wilk statistics using the *Proc Univariate* function of Statistical Analysis System software (SAS Institute, 1999). Non-normal data were transformed using log transformation. If the data from each landform segment approximated a normal distribution, parametric statistics were used to compare sediments, TP, TDP, and NO_3-N between landform segments. The results were evaluated using a one-way Analysis of Variance (ANOVA) using a least significant difference multiple comparison to assess the significance of the difference between pairs of landform segments (ANOVA results are reported in Appendix I). Year to year comparison of concentration and loads were done using t-tests. The significance level (α) was set at 0.05.

The influence of snowmelt runoff volume on nutrient load was studied by grouping daily runoff data for closed plots within each landform segment into two flow categories "high" and "low" based on the snowmelt runoff volumes. Based on visual judgment, daily runoff volumes of approximately 5 L in 2004 and 15 L in 2005 were used to group daily snowmelt runoff data from closed plots into the above two categories. These two categories were tested within each landform segment to study the influence of flow volumes.

5.6 Results and Discussion

5.6.1 Snow chemistry

Concentrations of snow N in NH_3 and NO_3-NO_2 forms were approximately equal to each other within and between both winters (Table 5.1). The ortho-P values ranged from 18% to 33% of the TP. The concentrations of ortho-P and TP were slightly higher in 2005 than in 2004 (Table 5.1).

Table 5.1 Nutrient concentrations in pre-melt snow samples[##].

		mg L^{-1}			
	n	NH_3-N	NO_3–NO_2-N	Ortho-P	TP
Winter 2004[#]	1	0.56	0.38	0.04	0.22
Winter 2005[†]	4	0.43 (19%)	0.40 (55%)	0.13 (73%)	0.40 (67%)

[##] CV values are reported in parenthesis. [#] Sampling was done on 09 March, 2004; [†] sampling was done on 27 March, 2005. n- Number of bulk snow samples submitted to the lab for nutrients analysis.

The sampling procedure adapted in this study results in values that provide average values which may not be uniform across the basin. The processes that are responsible for nutrient loading to snow (e.g., wind deposition, dry deposition from atmosphere) should be uniform across the landscape because of its small size and snow covered surrounding areas of this watershed. Therefore, similar nutrient concentrations of the snow in each landform segment could be realistic to expect even though the SWE is significantly different in the FS than the SH and the BS.

5.6.2 Snowmelt runoff water quality

The average concentrations, FW concentrations and average daily loads of the snow melt runoff water quality parameters (TP, TDP, NO_3-N, and sediment) estimated using the closed plots are presented in Table 5.2. Each average value in Table 5.2 gives a single representative value for the quality of snowmelt runoff generated within the watershed for the entire snowmelt runoff period.

Table 5.2 Average values of snowmelt runoff water quality parameters measured in 2004 and 2005 snowmelt runoff periods using the closed plots[##].

	2004		2005		
	Average[#]	CV	Average[#]	CV	P Value[¶]
TP Concentration (mg L^{-1})	2.3[a]	72%	1.5[b]	55%	0.009
FW TP concentration (mg L^{-1})	0.6[a]	146%	0.5[a]	101%	0.489
Daily TP Load (mg m^{-2} d^{-1})	6.1[b]	135%	18.6[a]	82%	3.5×10^{-5}
TDP Concentration (mg L^{-1})	2.2	43%	1.3	58%	
FW TDP Concentration (mg L^{-1})			0.4	86%	
Daily TDP Load (mg m^{-2} d^{-1})			15.6	82%	
NO_3-N Concentration (mg L^{-1})	5.2	54%			
FW NO_3-N Concentration (mg L^{-1})	1.2	106%			
Daily NO_3-N Load (mg m^{-2} d^{-1})	15.2	126%			
Sediment Concentration (mg L^{-1})	191[a]	105%	231[a]	97%	0.24
FW sediment Concentration (mg L^{-1})	40.6[a]	139%	69.6[a]	18%	0.06
Daily Sediment Load (mg m^{-2} d^{-1})	393[b]	121%	2242[a]	84%	3.5×10^{-11}

[##] FW – flow weighted; Number of observations was equal to 61 and 31 respectively in 2004 and 2005; The average duration of snowmelt runoff is 5 days for both snowmelt runoff periods. CV, coefficient of variations; [#] Means with same letters are not significantly different at α = 0.05. Lower case letter are used for mean comparison between the columns. [¶]From t-test.

In both years, sediment was the dominant concentration in the snowmelt runoff while the TDP had the lowest concentrations out of the four parameters tested (Table 5.2). Regression analysis between concentrations of these water quality parameters within a snowmelt period indicated that there was no significant relationship (data are not reported here) between water quality parameters, except between TP and TDP (R^2 = 0.92 and 0.93 respectively for 2004 and 2005). Therefore, concentrations of these water quality parameters (except TP and TDP) in snowmelt runoff are independent of each other and concentrations of one parameter can not be predicted using another parameter except for TP and TDP.

When comparing water quality parameters between the two snowmelt periods (2004 and 2005), it is important to remember that 2005 concentrations (including FW concentrations) were measured in approximately 3.6 times as much water as the 2004 concentrations since the average of the daily snowmelt runoff volume measured using 1 m^2 closed plots in the 2005 was 3.6 times greater than that in 2004. Thus more dilution should have occurred in 2005 than in 2004. The differences in the runoff volumes between years were also apparent in the average daily loads. For all of the nutrient parameters, the calculated FW concentrations were less than the average un-weighted concentrations indicating that the average concentrations are biased to high concentrations occurring during periods of low flow. Therefore, statistical comparisons of runoff water concentrations between the years should be interpreted with caution. Nutrient loads between the years can be safely compared since flow is a component of the load measurement.

In both spring melt periods, the average FW TP concentrations (Table 5.2) were much higher than the TP concentration (0.01 mg P L^{-1}) required for lakes and rivers in Canada to be classed as mesotrophic (Environment Canada, 2006) but were within the range of P concentrations (1.27 – 2.26 mg P L^{-1}) reported by Green (2001) for snowmelt runoff from a hog manured field within the South Tobacco Creek Watershed in Manitoba. The average FW NO_3-N concentration in 2004 was1.2 mg NO_3-N L^{-1} (Table 5.2) which was lower than the maximum acceptable concentration (10 mg NO_3-N L^{-1}) for NO_3-N in drinking water (Health Canada, 2006).

The FW sediment and FW TP in 2004 were similar to that of 2005 (Table 5.2) even with 3.6 times of dilution in 2005. The absence of a dilution effect in the 2005 P data indicates that there are sufficient available nutrients at the land surface to maintain concentrations even at the higher flow rates. Further, in 2005, the magnitudes of average daily loads of TP, and sediment from 1 m^2 area were greater than those observed in 2004 (Table 5.2). Higher nutrient and sediment loads in 2005 could be attributed to: (1) greater snowmelt runoff volume observed in 2005 than in 2004; (2) greater TP from snow because more of the snow was lost as runoff in 2005; and (3) higher flow rates in 2005 picking up more TP and sediment from the land surface.

For this watershed, the sources of the nutrients and sediment in the snowmelt runoff could be (1) from snow (direct contribution), and (2) from land surface (i.e. contribution due to interaction between soil and runoff water and from plant residues). The proportion of the nutrients that could have been derived from the snow cover can be estimated using a mass balance approach (Table 5.3). As daily nutrient release from the snow pack was not known, the percent nutrient contribution from snow for the entire snowmelt runoff period was estimated for each snowmelt runoff period using total runoff, average nutrient concentration of runoff, total water input by snow and nutrient concentration of snow.

Table 5.3 Estimation of percent nutrient contribution from snow.

Parameter	**TP** 2004	**NO_3-N** 2004	**TP** 2005
Total water input by snow (L)[##]	601×10^3		401×10^3
Total runoff (L)[##]	151×10^3		253×10^3
Runoff ratio (out of total water input)	0.25		0.63
Concentration in snow (mg L^{-1})	0.22	0.38[†]	0.40
Concentration in snowmelt runoff (mg L^{-1})	2.3	5.2	1.5
Total load from snow (mg)[#]	33×10^3	57×10^3	101×10^3
Total load in runoff (mg)	347×10^3	784×10^3	379×10^3
Percent contribution from snow	10%	7%	27%

[##] Depression was excluded for these estimations; [†] NO_3-NO_2-N concentration of snow was approximated to NO_3-N concentration in snow. # It was assumed that division of snow nutrients to snowmelt runoff and to infiltration was based on runoff ratio. Furthermore preferential nutrient release from snow pack and snow nutrient losses due to any other processes (i.e. deposition on the ground) were not considered to avoid complexity of estimations.

On average, snow contained the equivalent of 10% and 27% of TP in the snowmelt runoff respectively in 2004 and 2005 (Table 5.3). The higher TP contribution in 2005 from snow was due to a higher TP concentration of snow in 2005 than in 2004 and a higher runoff ratio in 2005 than in 2004 (Table 5.3). Snow contributed the equivalent of 7% NO_3-N of the snowmelt runoff in 2004 (Table 5.3). Usually the NO_2-N concentration is very small relative to NO_3-N and therefore, the NO_3-NO_2-N concentration of snow was used to approximate the NO_3-N concentration in snow. The rest of the nutrients in the snowmelt runoff should be from the land surface which includes both soil and plant residues. Based on this estimation, it is evident that the major part of nutrients in the snowmelt runoff is still from the land surface (i.e. from soil and/or from plant residues) irrespective of the year tested and the dominant hydrological process (e.g., infiltration versus runoff). Further, this proves that during the snowmelt runoff period, snowmelt runoff water interacts with the land surface to pick up nutrients and soils. The presence of sediment in snowmelt runoff for both years further supports this argument.

In both snowmelt runoff periods, TDP was the major portion of TP in snowmelt runoff. In 2004, 96 % of TP was TDP (comparison was done only using the runoff samples tested for TDP) while in 2005, 87% of TP was TDP. The average FW TDP concentration in 2005 was 0.4 mg L^{-1}. Ulén (2003) also reported a substantial amount of dissolved P in snowmelt runoff from a clay soil of central Sweden. Further, several studies reported that much of nutrient loss in snowmelt runoff was in soluble form (Harms et al., 1974; Burwell et al., 1975; Timmons and Holt, 1977).

The difference in snowmelt runoff water quality parameters between years could be due to a number of factors including: (1) influence of hog manure injections and soil nutrients in the fall; (2) winter conditions (i.e. freezing and thawing cycles, winter temperature, amount of snow); (3) hydrological processes during the spring melt (snowmelt runoff and infiltration); (4) interaction between the land surface and snowmelt runoff and; (5) dilution effects due to the volume of snowmelt runoff.

However, soil nutrient distribution in fall 2003 and fall 2004 did not reflect the snowmelt runoff water quality in the following springs. In fall 2003 after hog manure injection, the average available soil P (7 mg P kg^{-1} of soil) was lower than the average available soil P in fall 2004 (15 mg P kg^{-1} of soil). Therefore, a higher TP load in snowmelt runoff was expected for spring melt in 2005 because of the higher P availability in the top 5 cm of soil during fall 2004. However, because of the greater dilution in 2005 than in 2004, it is difficult to judge whether higher soil nutrient concentration causes higher TP concentration in snowmelt runoff. Further, as discussed before, higher snowmelt runoff flow was likely to pick up more nutrients and sediment. This further complicates the situation and makes it difficult to judge which one caused the higher TP load in 2005 (higher fall soil P versus higher runoff or both in 2005).

Linear regressions, nutrient concentration in snowmelt runoff versus nutrient concentration in soil and nutrient load in snowmelt runoff versus nutrient concentration in soil, were not significant (Table 5.4). This suggests that fall soil nutrient concentrations are not a dominant factor controlling the nutrients in the snowmelt runoff in this research site and indirectly suggests that snowmelt runoff volume controls the nutrient loads in snowmelt runoff. The significance of snowmelt runoff volume on nutrient loads can not be tested by simple linear regression as the runoff volume is a part of nutrient loads. Furthermore, significance of snowmelt runoff volume on nutrient concentration can not be tested by simple linear regression because of the systematic dilution effect (e.g., high runoff versus low concentration).

Table 5.4 Results of regression analysis for nutrient concentrations and loads in snowmelt runoff using fall soil nutrients.

Regression	2004 R^2	2004 $p^{\#}$	2005 R^2	2005 $p^{\#}$
TP concentration vs. soil P	0.02	0.6^{ns}	0.18	0.2^{ns}
TP load vs. soil P	0.22	0.1^{ns}	0.23	0.1^{ns}
NO-N concentration vs. soil NO_3^-	0.04	0.6^{ns}		
NO_3-N load vs. soil NO_3^-	0.08	0.3^{ns}		

$^{\#}$ *p – Probability;* ^{ns} *these regressions are not significant. Significant level (α) is at 0.05*

The daily variation of average concentrations of snowmelt runoff water quality parameters are presented in Figure 5.2. The average values of the TP and NO_3-N concentrations in snowmelt runoff had a decreasing trend with time in 2004 (Figure 5.2). This was likely due to dilution of TP and NO_3-N by the increasing flow rate in 2004 (Figure 5.2). In 2005, we did not observe the same trend between the time and TP in the snowmelt runoff as we observed in 2004. In 2005, snowmelt runoff rates fluctuated day by day (Figure 5.2) preventing the development of a temporal trend.

Sediment concentrations in 2004 were greatest on the second day of runoff then decreased for a few days before increasing towards the end of the event (Figure 5.2). Similarly, in 2005 sediment concentrations decreased from a high at the beginning of the event and then increased again in the later stages of the event. The initial decrease may reflect limited sediment availability while the increase towards the end may indicate some thawing of the surface soil. There was no apparent relationship between sediment concentration and flow (R^2 = 0.08, P = 0.2 and R^2 = 0.18, P = 0.2 respectively for 2004 and 2005).

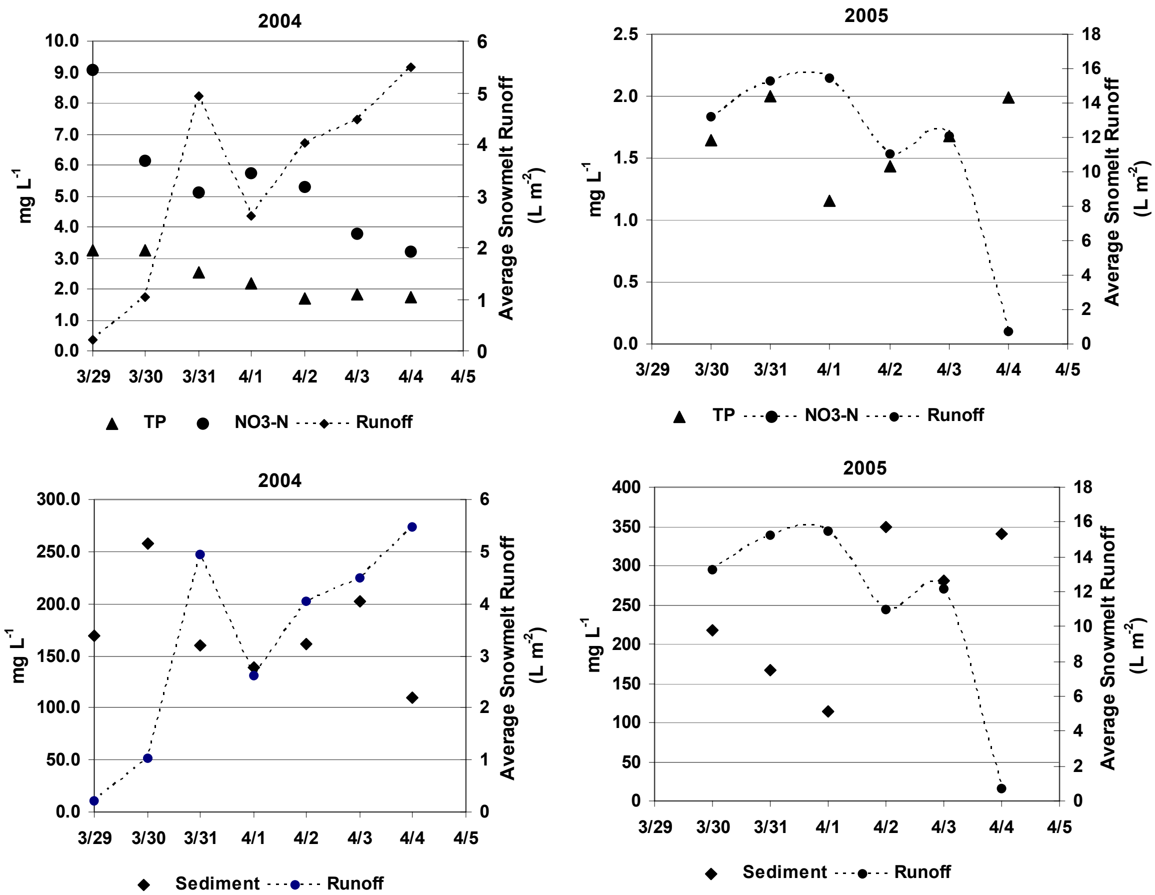

Figure 5.2 Temporal variations of average concentrations of snowmelt runoff water quality parameters and daily average snowmelt runoff flow rates.

5.6.3 Snowmelt runoff water quality versus landform segments

Average values of the water quality parameters of the snowmelt runoff generated within 1 m^2 areas at different landform segments are compared in Table 5.5. Statistical comparisons for 2004 data were done for the period where all landform segments had runoff. However, in 2005 the FS segment was not considered for statistical comparison as it was inundated by runoff water after the first day of runoff.

Table 5.5 Means of snowmelt runoff water quality parameters for three landform segments in 2004 and 2005 (closed plots).

	2004				2005		
Parameter	FS[#]	BS[#]	SH[#]	F/P Value[¶]	BS[#]	SH[#]	F/P Value[¶]
TP (mg L^{-1})	3.0 [a]	1.7 [a]	2.7 [a]	2.6/0.10	1.5 [a]	1.3 [a]	0.1/0.72
FW TP (mg L^{-1})	2.6 [a]	1.2 [a]	2.6 [a]	2.4/0.12	1.3 [a]	1.5 [a]	0.2/0.70
TP Load (mg m^{-2})	20.9 [a]	19.0 [a]	26.5 [a]	0.3/0.75	72.2 [a]	39.8 [a]	0.5/0.49
TDP (mg L^{-1})					1.3 [a]	1.1 [a]	0.3/0.61
FW TDP (mg L^{-1})					1.2 [a]	1.3 [a]	0.04/0.85
TDP Load (mg m^{-2})					63.7 [a]	33.4 [a]	0.6/0.45
NO_3-N (mg L^{-1})	5.8 [a]	4.4 [a]	5.2 [a]	1.5/0.25			
FW NO_3-N (mg L^{-1})	5.2 [a]	3.3 [b]	4.7 [a]	4.6/0.02			
NO_3-N Load (mg m^{-2})	41.1 [a]	69.5 [a]	55.1 [a]	0.4/0.67			
Sediment (mg L^{-1})	246.2[a]	142.2 [a]	187.5 [a]	0.9/0.39	190.0 [a]	328.2 [a]	1.2/0.31
FW Sediment (mg L^{-1})	168.6[a]	125.2 [a]	144.2 [a]	0.2/0.81	184.3 [a]	268.3 [a]	1.1/0.33
Sediment Load (mg m^{-2})	1091[a]	1767 [a]	1407 [a]	0.8/0.46	9509 [a]	5422 [a]	1.1/0.33

FS – footslope, BS – backslope, SH-shoulder; FW – flow weighted; [#] Means with same letters are not significantly different at α = 0.05. Lower case letter are used for mean comparison between the columns within each year. [¶]From ANOVA table. F, F statistics from ANOVA table; P, probability of F statistics from ANOVA. In 2005, the FS was not compared with SH and BS because of flooding. In 2004, load from the footslope was incomplete because load in runoff after the outlets were inundated was not included in the calculation.

The water quality parameters (i.e. concentration, FW concentration and load of TP, TDP, NO_3-N and sediment) did not differ between the landform segments within a year (Table 5.5) except for FW NO_3-N concentrations on the BS segment in 2004. Flow weighted concentration of NO_3-N was lower in snowmelt runoff from the BS segment than from the other two segments in 2004. However, there is no apparent reason to explain lower FW NO_3-N concentrations at the BS. Based on nutrient concentrations and loads (Table 5.5), it is evident that landform segments do not influence the water quality of snowmelt runoff generated within unit areas of the landform segment.

Regression analysis of nutrient concentrations in snowmelt runoff versus fall soil nutrient concentrations and nutrient load in snowmelt runoff versus fall soil nutrient concentration for each landform segment revealed no relationships (R^2 values are not reported here) in both 2004 and 2005. Therefore, no general effects of fall soil nutrients on the corresponding nutrient concentration and load in snowmelt runoff were observed at the landform segments scale.

The effect of snowmelt runoff volume on nutrient load was tested using daily runoff data grouped into two flow categories "high" and "low" based on the snowmelt runoff volumes within each landform segment. Within each landform segment, fall soil nutrient concentrations were assumed to be similar for both flow categories. Therefore, if there is a difference in nutrient load between these two flow categories within each landform segment, it should be due to the influence of runoff volume on nutrient load. Figure 5.3 further supports this argument. In Figure 5.3, a higher nutrient load in the high flow category results only when more nutrients are transported in the high flow category than in the low flow category.

The average daily TP, NO_3-N and sediment loads were higher in the high flow category than in the low flow category for each landform segment irrespective of the year tested except the sediment in the SH (Table 5.6).

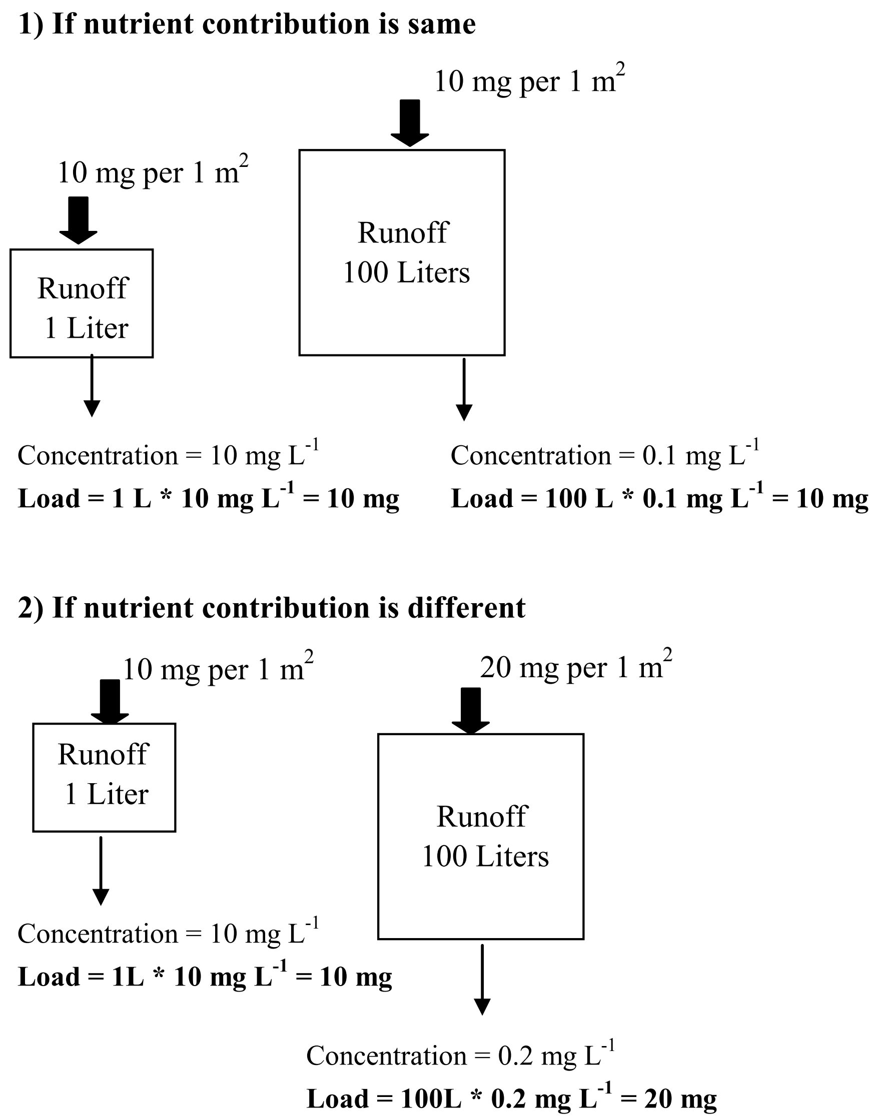

Figure 5.3 Conceptual model to illustrate the influence of runoff volume on nutrient load.

Table 5.6 Average daily load of nutrients and sediment for low and high flow [#].

		Average flow ($L\ d^{-1}$)		TP ($mg\ m^{-2}\ d^{-1}$)		NO_3-N ($mg\ m^{-2}\ d^{-1}$)		Sediment ($mg\ m^{-2}\ d^{-1}$)	
		Low	High	Low	High	Low	High	Low	High
2004	BS	1.2	11.7	1.5^b	10.7^a	3.9^b	39.7^a	165^b	911^a
	SH	2.2	7.7	5.8^b	14.1^a	10.0^b	43.7^a	357^a	437^a
2005	BS	11.2	26.8	17.6^b	32.2^a			2309^b	4303^a
	SH	7.6	25.5	14.2^b	$22.7b^a$			1762^a	1990^a

[#] In 2004, daily runoff volumes lower than or equal to 5 L were grouped into "Low" category while the rest were grouped into "High" category. In 2005, daily runoff volumes lower than or equal to 15 L were grouped into "Low" category while the rest were grouped into "High" category. Means with same letters are not significantly different at α = 0.05. Lower case letter are used for mean comparison between the columns within each parameter.

The higher TP and NO_3-N loads in the high flow category were not due to the higher sediment load in this category (Table 5.6) as most of the TP and NO_3-N was in dissolved form. Further, the average concentrations of TP, NO_3-N and sediment in the high flow category were always similar or lower than those in the low flow category (Table 5.7) . Lower concentrations observed in the high flow category (Table 5.7) were due to the dilution of available nutrients by high flow volumes. However, despite some dilution, high flows consistently resulted in greater nutrient and sediment transport.

Table 5.7 Average daily concentrations for high and low flow[#].

		TP ($mg\ L^{-1}$)		NO_3-N ($mg\ L^{-1}$)		Sediment ($mg\ L^{-1}$)	
		Low	High	Low	High	Low	High
2004*	BS	2.0^a	1.0^a	4.6^a	4.1^a	185.7^a	82.0^b
	SH	2.8^a	2.0^a	5.4^a	5.7^a	196.6^a	67.6^b
2005*	BS	1.6^a	1.3^a			210.1^a	185.3^a
	SH	1.6^a	0.9^a			318.0^a	86.7^b

[#]In 2004, daily runoff volumes lower than or equal to 5 L were grouped into "Low" category while the rest were grouped into "High" category. In 2005, daily runoff volumes lower than or equal to 15 L were grouped into "Low" category while the rest were grouped into "High" category. Means with same letters are not significantly different at α = 0.05. Lower case letter are used for mean comparison between the columns within each parameter.

The total load of nutrients and sediment from the SH (i.e., total runoff of the landform segment × FW concentration) was the highest in this watershed while BS contributed the least (Table 5.8). However, the total load per hectare [i.e., (total load (kg) ÷ area of the landform segment (m^2)) ×10000 (m^2/ha)] of each landform segment increases in the down slope direction irrespective of the year except for TP load for BS in 2004 (Table 5.8). This increase can be attributed to the increasing ratio between water inputs and the areas of the landform segment in the downslope direction. In terms of total mass contributed, the SH is the biggest overall contributor of nutrients and sediment (Table 5.8) as the SH area occupies approximately 68% of the total watershed area. Therefore, the total area of each landform segment is also an important factor for snowmelt runoff water quality.

Table 5.8 Total loads and total load per hectare from each landform segment.

	2004			2005		
Parameter	FS[#]	BS[#]	SH[#]	FS[#]	BS[#]	SH[#]
Total TP Load (kg)	0.11	0.03	0.16		0.09	0.28
Total TP Load (kg ha^{-1})	1.29	0.23	0.29		0.65	0.50
Total NO_3-N load (kg)	0.22	0.09	0.29			
Total NO_3-N Load (kg ha^{-1})	2.58	0.64	0.53			
Total Sediment load (kg)	7.11	3.38	9.08		12.72	50.44
Total Sediment Load (kg ha^{-1})	83.8	24.38	16.21		91.75	89.97

[#]FS – footslope, BS – backslope, SH-shoulder. Footslope load was calculated using the FW average concentration in the first few days of runoff with the total amount of runoff estimated to have occurred on the footslope during the whole event.

The Loads in Table 5.8 have been calculated using FW concentration and total runoff. This method (used in table 5.8) resulted in loads similar to the values estimated using water quality data in the depression (data are not reported here). However, the loads given in Table 5.8 are slightly different from the loads reported in Table 5.5 because of the way the loads in Table 5.5 have been estimated. The loads in Table 5.5 represent the mean value of total load from each 1 m^2 plot (6 plots per landform segment). Total load for each plot was calculated as the sum of daily loads (i.e.; product of runoff volume of concentration). For example, if the plot produced runoff for 5 days, then the total load for the plot was equal to sum of day 1 load , day 2 load , day 3 load, day 4 load and day 5 load.

5.6.4 Influence of run-on on snowmelt runoff water quality

Influence of run-on on snowmelt runoff water quality was studied using the open plots established in both years in this study. Open and closed plots were compared using only paired plots which produced runoff at the BS to understand the influence of run-on on snowmelt runoff water quality.

In 2004, average TP, NO_3-N and sediment concentrations were not significantly different between the closed and the open plot (Table 5.9) but FW concentrations and daily average loads of these quality parameters were significantly different (Table 5.9). Because of the greater dilution effect in the open plots than in closed plots, it is not surprising that there were no significant differences in un-weighted concentrations. While the greater nutrient load from the open plots can simply be attributed to the greater flow volumes from open plots, the significantly different flow-weighted concentrations of the water quality parameters indicates that the run-on water was affecting nutrient and sediment concentrations. Either the run-on water contained higher concentrations of nutrients than the runoff generated within the plot or the presence of run-on caused more nutrients and sediments to be picked up by snowmelt runoff on its way through the plot. Since FW NO_3-N were significantly higher in runoff from the SH segment than from the BS segment in 2004 (Table 5.5), the run-on water would likely have contained a higher concentration of NO_3-N. But this is not valid to FW TP and FW sediment concentrations, as there was no significant difference between the BS and SH segments in terms of FW TP and FW sediment concentrations (Table 5.5). Therefore a higher nutrient load in run-on water was likely due to: (a) the run-on water contained higher concentrations of nutrients than the runoff generated within the plot (in the case of NO_3-N); and (b) the presence of run-on caused more nutrients and sediments to be picked up by snowmelt runoff on its way through the plot (in the cases of TP and sediment).

In 2005, when there were greater runoff volumes and no significant differences in water quality between the SH and BS positions, there were no significant differences in water quality between the open and closed plots (Table 5.9). Despite significantly greater runoff from the open plots than the closed plots in 2005, the nutrient and sediment loads from the open plots and the closed plots were not significantly different and this was likely due to the reduction in contributing area to open plots in 2005. In 2004, the equivalent of 3 closed plot areas (i.e., 59.4×10^{-3} $m^3 \div 19.8\times10^{-3}$ m^3 m^{-2}) contributed runoff to the open plots, while in 2005, the equivalent of 1.3 closed plot areas contributed runoff (i.e., 65.4×10^{-3} $m^3 \div 49.7\times10^{-3}$ m^3 m^{-2}). This reduction could have been due to ice on the ground in snowmelt runoff dominated year (2005) than in infiltration dominated year (2004). The presence of ice on the ground could have blocked the runoff to the open plots.

Table 5.9 Means of snowmelt water quality parameters for open and closed plots in 2004 and 2005 (values represent the averages for the entire snowmelt runoff period).

	2004#			2005#		
Parameter	Open plot	Closed plot	P Value¶	Open plot	Closed plot	P Value¶
TP (mg L^{-1})	2.4 a	1.6 a	0.06	1.3 a	1.6 a	0.32
FW TP (mg L^{-1})	2.4 a	1.1 b	0.05	1.2 a	1.3 a	0.78
TP Load (mg d^{-1})	30 a	5 b	0.0002	24 a	22 a	0.72
TDP (mg L^{-1})				1.1 a	1.4 a	0.29
FW TDP (mg L^{-1})				1.0 a	1.2 a	0.74
TDP Load (mg d^{-1})				21 a	19 a	0.76
NO_3-N (mg L^{-1})	5.5 a	4.3 a	0.07			
FW NO_3-N (mg L^{-1})	5.1 a	3.5 b	0.01			
NO_3-N Load (mg d^{-1})	73 a	19 b	0.0009			
Sediment (mg L^{-1})	152.1 a	141.6 a	0.70	202.8 a	196.0 a	0.92
FW Sediment (mg L^{-1})	149.4 a	127.6 b	0.05	172.5 a	173.1 a	0.99
Sediment Load (mg d^{-1})	1875 a	477 b	0.001	32023 a	2739 a	0.67

Means with same letters are not significantly different at $\alpha = 0.05$ within a sample year. Lower case letter are used for mean comparison between the columns within a sample year; FW – flow weighted; only paired plots at the BS are included here. ¶*From t-test.*

5.7 Conclusions

Snowmelt runoff water quality measured using closed plots varied within and between the years tested. The average FW TP concentration of the snowmelt runoff in 2004 and 2005 were 0.6 mg L^{-1} and 0.5 mg L^{-1} which were higher than the Canadian water quality standards. In both snowmelt runoff periods, the major portion of runoff TP was accounted for by the TDP. On average the TDP concentration in snowmelt runoff accounted for 96% of the TP. The average FW NO_3-N concentration in 2004 was 1.2 mg L^{-1} and this is below the Canadian water quality standard despite the manure injection in fall 2003. The average FW sediment concentrations in 2004 and 2005 spring melts were 40.6 mg L^{-1} and 69.6 mg L^{-1} respectively. Daily average loads of TP and sediment were greater in 2005 than in 2004. Manure injection below soil-runoff interactive layer in the fall did not seem to influence snowmelt runoff water quality in the immediate spring.

The maximum nutrient contribution from snow to snowmelt runoff varied with the year and the nutrient types. On average, snow nutrients contained the equivalent of 10% and 27% of TP of the snowmelt runoff respectively in 2004 and 2005. Snow contained the equivalent of 7% of NO_3-N in the snowmelt runoff in 2004. The rest of the nutrient load in the snowmelt runoff was likely due to the interaction of snowmelt runoff with the land surface. However, fall soil nutrient concentrations did not reflect either in the nutrient concentrations or nutrient loads in snowmelt runoff in both snowmelt runoff periods. Instead, snowmelt runoff volume controlled snowmelt runoff water quality. Higher runoff volumes always generated higher nutrients and sediments loads in snowmelt runoff irrespective of the landform segment, and the year.

Snowmelt runoff water quality did not vary between the landform segments in this undulating landscape in both snowmelt runoff periods. However, the SH was the biggest nutrient and sediment contributor to the depression in terms of total mass because of its greater area compared to the other landform segments in this watershed. The BS contributed the least mass of nutrients and sediments because of its lowest runoff volume. Further, the total mass of nutrients and sediment per hectare of each landform segments increased in the downslope direction because of increasing runoff volumes in the downslope direction. Influence of run-on on snowmelt runoff quality and quantity was observed only when the snowmelt infiltration was the dominant hydrological process.

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CHAPTER 6

Synthesis and Conclusions

6.1 Introduction

Rainfall runoff water quality is governed by a combination of transport factors (such as runoff and erosion) and source factors (such as soil nutrients and manure). The influence of these transport and source factors on rainfall runoff water quality is well documented. However, snowmelt runoff water quality has not been studied as extensively as rainfall runoff water quality and therefore, factors that control snowmelt runoff water quality are not clear. The presence of nutrients in snowmelt runoff has been reported by previous studies, but, none of these studies have identified the areas within the watershed that contribute nutrients to snowmelt runoff (critical source areas or CSA).

Our understanding of rainfall runoff water quality and it's governing factors can not be directly applied to snowmelt runoff water quality in the Canadian prairies as snowmelt runoff is fundamentally different from rainfall runoff. Therefore, important questions in relation to snowmelt runoff quality are still remaining: (1) does snowmelt runoff interact with soil in the Canadian prairies where the snowmelt runoff period lasts less than a week and the soil is still frozen; (2) are both source and runoff factors equally important for snowmelt runoff water quality; (3) can poor snowmelt runoff water quality be expected from the areas with higher fall soil nutrient concentrations; (4) do high snowmelt runoff rates result in poorer runoff water quality; and (5) what areas of the watershed contribute nutrients to snowmelt runoff? These fundamental questions must be answered to understand the influence of source and transport factors on snowmelt runoff water quality and enable its sustainable management in the Canadian prairies.

This study was designed to find the answers to the above fundamental questions and to understand the importance of source and transport factors on snowmelt runoff water quality in the Canadian prairies. Based on the findings of this study, it is evident that;

1. Snowmelt runoff interacts with the land surface and picks up nutrients and sediments from the land surface (Section 5.6.2). Land surface includes soil and crop residues.

2. The land surface is the major nutrient and sediment contributor to the snowmelt runoff (Section 5.6.2). Snow itself contributes a significant proportion of total nutrients in snowmelt runoff (Section 5.6.2). Therefore, the major sources of nutrients to snowmelt runoff are; soil, manure, crop residues, and snow (Figure 6.1).

3. Most nutrients in snowmelt runoff are in the dissolved form (Section 5.6.2 and Table 5.5). Therefore, the nutrients in snowmelt runoff from each landform segment have a high potential to move with snowmelt runoff without settling out before reaching the receiving waters.

4. A combination of nutrient sources and snowmelt runoff determine the quality of snowmelt runoff (Figure 6.1). However, fall soil nutrient concentrations in the top 5 cm layer of soil in each landform segment are not the dominant factor

controlling the nutrients in the snowmelt runoff (Section 3.6.3 and 3.6.4). Snowmelt runoff volume in each landform segment (Section 4.6.4) is the dominant factor that controls snowmelt runoff water quality (Table 5.2 and Section 5.6.3).

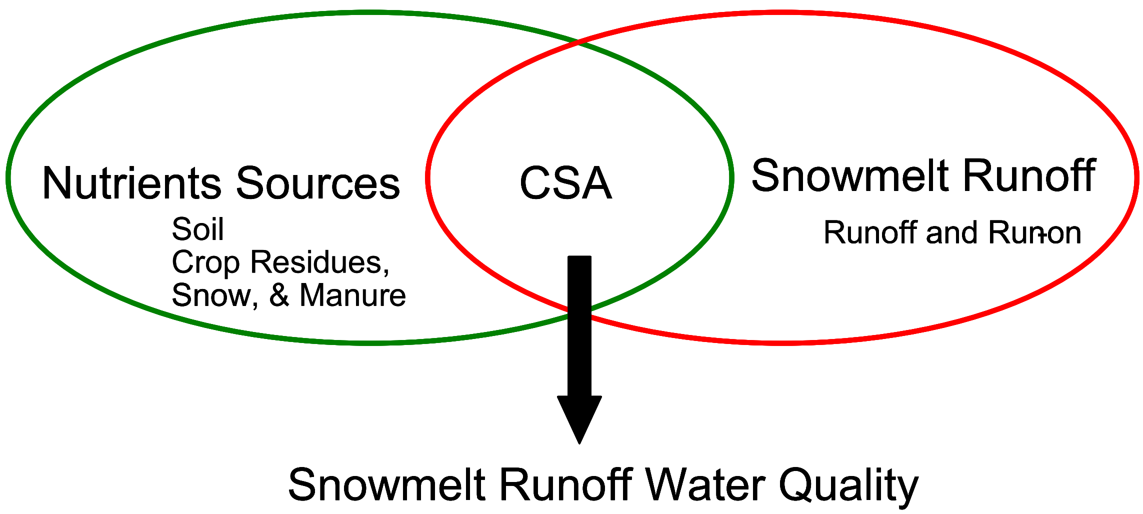

Figure 6.1 The source and transport factors that control snowmelt runoff water quality.

5. Higher runoff volumes always generate higher nutrient and sediment loads (Tables 5.6 & 5.7) in snowmelt runoff irrespective of the landform segment, and dominant hydrological process (e.g., infiltration in 2004 and snowmelt runoff in 2005). Therefore, higher nutrient and sediment loads are expected from the downslope areas of the watershed as the runoff volume is greater in downslope areas (e.g., footslope) than in upslope areas (e.g., shoulder) of the landscape (Figure 6.2).

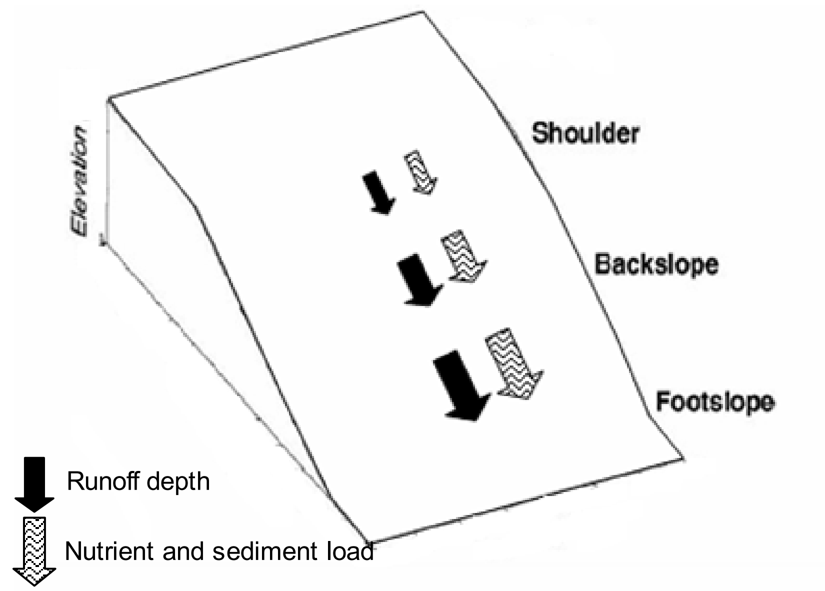

Figure 6.2 Conceptualized model for nutrient/sediment load released to snowmelt runoff based on snowmelt runoff volume alone. (*The size of the arrows indicates the relative amount of nutrient/sediment load and snowmelt runoff depth*).

6. The influence of higher fall soil nutrient concentrations on snowmelt runoff water quality could not be tested in this study because the ranges of fall soil nutrient concentrations in the top 5 cm layer of soil in this landscape were small even with manure injection into 10-12 cm depth of soil (Table 3.5, 3.6 and 3.7). However, a higher nutrient load in snowmelt runoff can be expected from areas with higher nutrient concentrations as; (a) it is evident that snowmelt runoff interacts with the land surface; and (b) the major portion of nutrients in snowmelt runoff is from the land surface.

7. The relative area covered by each landform segment is important when assessing the total nutrient load from each landform segment. A landform segment with a relatively small nutrient load per unit area may be important if the area of the segment is significantly greater than that of the other segments.

The presence of nutrients in snowmelt runoff is a result of the transport factor (snowmelt runoff) interacting with source factors (nutrients from soil, manure, crop residues, and snow) and picking up nutrients from these sources. Therefore, snowmelt runoff water quality (i.e., nutrient concentrations and loads) in each landform segment is governed by a combination of source and transport factors as for rainfall runoff water quality (Figure 6.1). Source factors (nutrients from soil, manure, crop residues, and snow), the transport factor (snowmelt runoff) and the extent of the contribution area are important factors in determining the total nutrient load from each landform segment.

6.2 Identification of critical source areas

The areas that contribute nutrients to snowmelt runoff are defined as critical source areas (CSA). In CSA, snowmelt runoff water quality (i.e., nutrient concentrations and loads) is governed by the combined effect of source and transport factors (Figure 6.1). Therefore, the following conceptual model (Figure 6.3) describes interactions between source and transport factors and can be used to; (a) identify the CSA, and (b) rank the CSA (the landform segments) based on their relative nutrient loads released as snowmelt runoff.

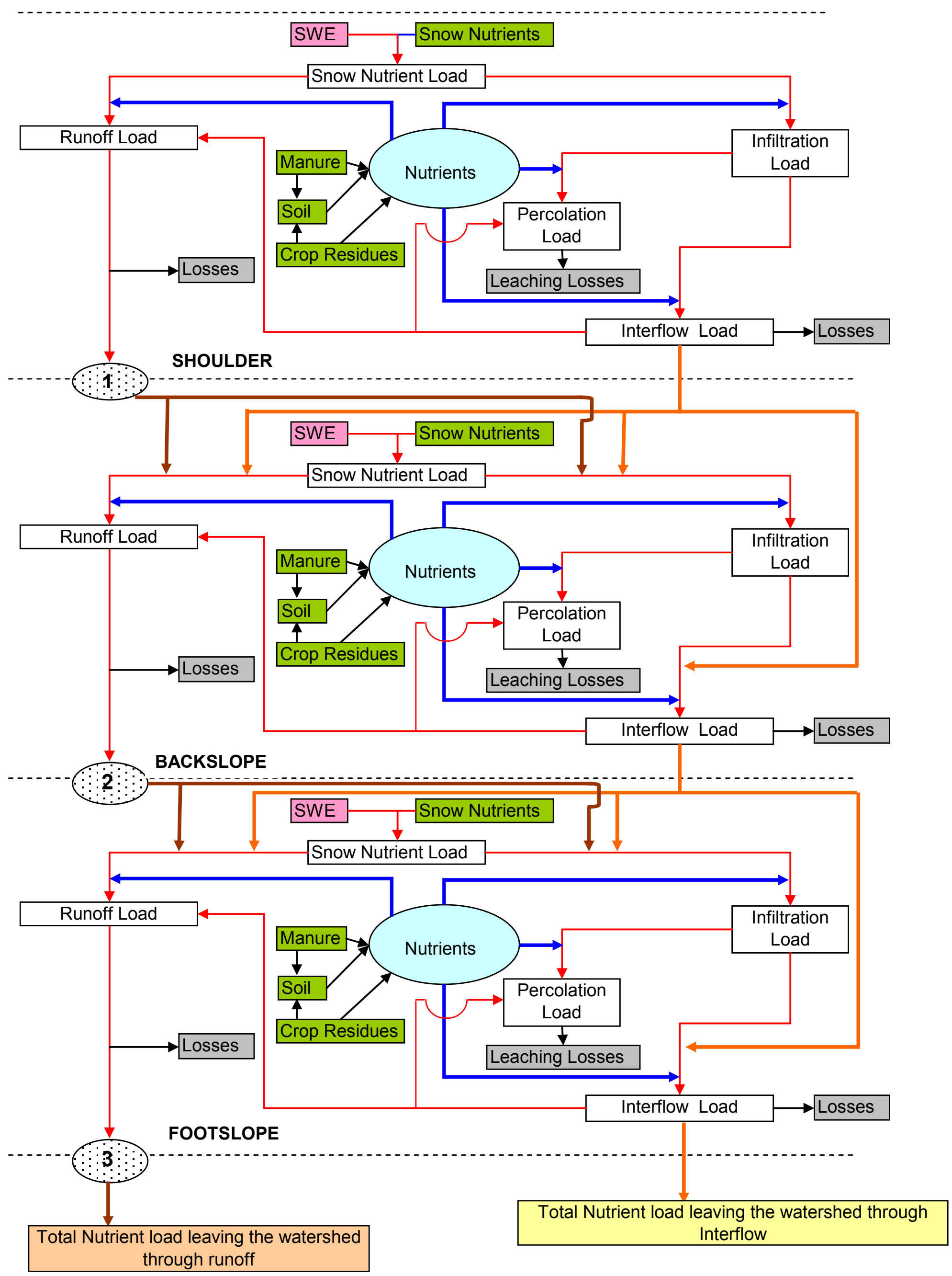

Figure 6.3 The Conceptual model to identify critical source areas.(*Blue arrows, interactions between nutrient sources and transport processes; red arrows, flow of nutrient load; brown arrows, run-on as surface flow; orange arrows, run-on as interflow; green boxes, nutrient sources; white boxes, nutrient load in different transport processes; gray boxes, nutrient losses; small ovals, cumulative nutrient load at the edge of each landform segment; large ovals, nutrients available for transport in each landform segment).*

6. 2.1 Features of the conceptual model

1. Nutrient load per unit area from each landform segment is determined by the interaction of source and transport processes within the landform segment. Therefore, separate loops for nutrient sources (e.g., nutrients from soil, manure, snow, and crop residues) and transport processes (e.g., runoff, run-on and interflow) are incorporated for each landform segment to allow for variation between the landform segments and between snowmelt runoff periods.

2. The model considers the transport processes and interactions (between nutrient sources and transport processes) within a shallow surface layer (top 5 cm of soil) during the snowmelt runoff period.

3. For each landform segment, four hydrological-nutrient interaction terms have been introduced; (a) interaction between surface runoff and nutrient sources; (b) interaction between infiltration and nutrient sources; (c) interaction between interflow (i.e. water flow within a shallow sub-surface layer roughly parallel to the soil surface) and nutrient sources; and (d) interaction between percolation (i.e. water moving downward) and nutrient sources. Percolation does not contribute to surface runoff within any of the landform segments and thus, nutrients in percolation are considered as a loss from the hill-slope runoff system.

4. Losses of nutrients and water from each landform segment are introduced to the main transport processes of runoff and interflow. These losses are attributed to; (a) nutrient loss due to chemical and biological processes; (b) gaseous losses of nutrients; and (c) water losses due to evaporation, soil storage and storage in micro-topographic depressions within the landform segments.

5. Nutrient load at the downslope edge of each landform segment (1, 2 and 3 of Figure 6.3) represents the cumulative nutrient load at the bottom of each successive landform segment including the upslope segments. Therefore, total nutrient load from the shoulder, backslope, and the footslope will be equal to 1, (2-1) and (3-2) respectively.

6. Landform segments in upslope areas (e.g., shoulder) influence the downslope landform segments (e.g., backslope or footslope) through snowmelt runoff, and interflow. Therefore total runoff from the downslope landform segment is the sum of runoff from that landform segment and run-on and interflow from the upslope segment.

6.2.2 Application of the conceptual model for different situations

Even though many different situations can be considered, only the following scenarios are chosen here to enhance the findings of this study and to illustrate how the proposed conceptual model would be used to; (a) simulate nutrient loads from each landform segment, (b) identify CSA, and (c) understand their relative importance. These situations are chosen because they are very relevant to the Canadian prairie conditions. During the following discussion, all the conditions between the landform segments are assumed to be similar except for the conditions reported in the scenario.

Scenario 1: Absence of snow in the shoulder due to wind erosion

As reported in section 4.3.1, the shoulder is subjected to greater snow erosion by wind because of its location in the landscape. Therefore, the complete absence of snow or having not enough snow to generate snowmelt runoff in the shoulder is possible in the prairie landscape.

In the absence of snow on the shoulder, there are no transport processes (e.g., snowmelt runoff) within the shoulder and no nutrients coming out of the shoulder. Therefore, the shoulder is not a CSA under this condition. The loop of the conceptual model (Figure 6.3) that estimates final nutrient load from the shoulder can be removed from the model.

The backslope and the footslope are still CSA in this scenario assuming that there is runoff from both landform segments. The snowmelt runoff volume available to interact with nutrient sources increases downslope in the landscape because the footslope has generally greater SWE than the backslope (in general, more snow accumulates in footslope positions in the landscape). Since snowmelt runoff volume is the dominant factor influencing nutrient load, the footslope will produce greater nutrient load per unit area than the backslope. In addition, snowmelt runoff from the backslope adds to the runoff in the footslope as run-on and may pick up more nutrients on the footslope segment. Therefore, when nutrient load per unit area is considered, the footslope will be the most important CSA while the backslope is the least important CSA. However, as the backslope area is much greater than the footslope area, the total nutrient load from the backslope (e.g., 2 in Figure 3.6) can be greater than the total nutrient load in the footslope (e.g., [3-2] in Figure 3.6). Therefore, from the perspective of total nutrient load, the backslope is the most important CSA in the landscape for this scenario.

Scenario 2: Enhanced snowmelt infiltration in the shoulder by fall tillage

On the Canadian prairies, manure application onto agricultural lands is increasing. Any fall tillage operation or fall manure injection has the potential to enhance the infiltration during the melting period because of macro-pores created during the tillage operation.

If enhanced infiltration occurs only in the shoulder because of fall tillage, it will reduce snowmelt runoff from the shoulder and thus, the nutrient load per unit area. Part of the infiltrated water may add to the snowmelt runoff as interflow within the shoulder or in a downslope segment. Water from interflow may have gained nutrients due to interaction with nutrient sources in the soil. Reduced snowmelt runoff from the shoulder will further reduce the nutrient loads per unit area from the backslope and the footslope through the reduction in run-on to the downslope segments. Under this scenario, all the landform segments are critical as all of them contribute nutrients to snowmelt runoff. However, their relative importance will increase in the downslope direction as the nutrient load per unit area from each landform segment increases in the downslope direction as explained in scenario 1. The proposed conceptual model (Figure 6.3) is capable to capture above changes under this scenario.

The shoulder of the study watershed was the most important CSA from the perspective of total nutrient load as it produced the largest total nutrient load in both 2004 and 2005 because its contributing area was larger than those of other landform segments (Table 5.8). If enhanced infiltration reduced runoff from the shoulder sufficiently, the total nutrient load from the shoulder could drop to a level below that from the other landform segments. Under this situation, the relative importance of landform segments as CSA for total nutrient load might change depending degree to which runoff volume from the shoulder is impacted by fall tillage.

Scenario 3: Variable rate of manure application to different landform segments

Variable rate hog manure application has potential as a beneficial management practice for the protection of surface water quality. Therefore, an important application of the conceptual model is to assess the impact of different distributions of manure application on nutrient load in snowmelt runoff.

Applied manure provides nutrients to snowmelt runoff within each landform segment and variable distributions of applied manure can be simulated using the proposed conceptual model (Figure 6.3) as nutrients from different sources are considered separately for each landform segment.

If manure application does not raise soil nutrient levels beyond the range observed in this study (Chapter 3), the impact of manure addition will be minimal and the total nutrient load from each landform segment will continue to be determined largely by the snowmelt runoff volume and the extent of the land area. However, if manure application is excessively high, the nutrient source will have a greater influence on nutrient load. If this happens, the distribution of manure addition between landform segments, runoff volume and the size of contributing area of the landform segments will determine the relative importance of each landform segment as a CSA for total nutrient load. If manure is preferentially applied to any landform segment at excessive rates, the relative importance of that segment as a CSA will likely increase.

Scenario 4: Change from pothole to dissected landscape

Not all prairie landscapes have the same distribution of landform segments as found at the study site. In the pothole landscape of the study area, shoulders are the dominant landform segment but in dissected landscapes long backslopes generally dominate the landscape and shoulder and footslope segments occupy a relatively small portion of the land area.

If the nutrient load per unit area from the landform segments in this scenario is assumed to be the same as for the study site, the relative importance of the CSA from a total nutrient load perspective will change with the change in landscape. The shoulder will no longer be the most important CSA as it will have a lower nutrient load per unit area and a lower area than the backslope. The relative importance of the footslope and backslope segments in total nutrient load contribution will depend on the relative magnitude of the difference in area (backslope > footslope) and the difference in nutrient load per unit area (footslope > backslope) between the segments.

However, the nutrient load per unit area may also change with the change in landscape as the run-on from the shoulder to the backslope will be reduced while the run-on from the backslope to the footslope will likely increase. The implications of these changes can also be investigated using the proposed conceptual model.

Scenario 5: Thin ice layer on footslope segment

The presence of a thin ice layer on the land surface during the snowmelt runoff is possible in the Canadian prairies. Mid-winter melting can create a layer of ice on the soil surface. The impact of the ice layer can be evaluated with the conceptual model.

An ice layer on the footslope will reduce infiltration and prevent snowmelt runoff from interacting with soil and picking up nutrients from soil within the footslope segment. However, nutrients from snow and crop residue can still contribute nutrients to snowmelt runoff. Since the conceptual model has separate simulation loops for different nutrient sources within the footslope (Figure 6.3), the nutrient load from the footslope can still be simulated for this scenario. However, as the land surface usually contributes the major portion of nutrients to snowmelt runoff and there is no interaction between snowmelt runoff and soil within the footslope, the footslope will be the least important CSA for both nutrient load per unit area and total nutrient load in this situation.

6.3 Conclusions

Based on the analysis of the proposed conceptual model, the following can be concluded on CSA and their relative importance.

1. All the landform segments are critical source areas when both source (nutrients from soil, manure, crop residue and snow) and transport factors (snowmelt runoff) are present and interact within each landform segment.

2. The relative importance of CSA (landform segments) varies with the conditions within each landform segment and depends on environmental and management factors that influence (a) partitioning between runoff and infiltration, (b) the relative distribution of SWE, (c) nutrient source availability for each landform segment, and (d) the relative areas of the landform segments. Environmental factors may include winter weather conditions (that impact snow distribution or ice layer formation), and landscape type. Some examples of management factors are manure or fertilizer applications (including variable rate), fall tillage and stubble management.

3. Under similar conditions for each landform segment, the relative importance of CSA increases in the downslope direction because the snowmelt runoff volume generated in the downslope segments is augmented with run-on from upslope segments which may gain additional nutrients in the downslope segment.

6.4 Suggestions for future work

The following suggestions are made for any future work involving snowmelt runoff water quality.

1. The nutrient contribution from crop residues during the snowmelt runoff period in Canadian prairies should be studied to understand the source factors impacting snowmelt runoff water quality.

2. Studies are needed to understand how and to what degree snowmelt runoff interacts with the soil layer especially during the short snowmelt runoff period that occurs within the Canadian prairies and to estimate the thickness of the soil layer which interacts with snowmelt runoff. At the same time, fall soil nutrient concentrations at different depths (e.g., 5, 10, 15, 20 cm) and along the landscape should be studied and their influence on snowmelt runoff water quality should be evaluated.

3. The applicability of these research findings should be tested in other landscapes.

4. A study should focus on soil nutrient transport with over winter soil moisture migration. Furthermore, the relationship between fall soil nutrient concentration and soil nutrient concentration just before melting should be studied.

5. A study on the relative importance of interflow to runoff volume and nutrient contribution to runoff should be conducted on the Canadian prairies.

APPENDIX I

ANOVA results for Table 3.3

Single factor for TN

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4638907	2	2319454	55.18908	1.21E-07	3.68232
Within Groups	630411	15	42027.4			
Total	5269318	17				

Single factor for TP

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	251430.6	2	125715.3	59.40084	7.45E-08	3.68232
Within Groups	31745.84	15	2116.389			
Total	283176.4	17				

Single factor for TC

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10.35218	2	5.176089	38.04815	1.33E-06	3.68232
Within Groups	2.040607	15	0.13604			
Total	12.39278	17				

Single factor for OC

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.497098	2	4.248549	36.47037	1.73E-06	3.68232
Within Groups	1.747398	15	0.116493			
Total	10.2445	17				

ANOVA results for Table 3.4

Single factor for soil moisture in 2003 fall

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	21.88315	2	10.94157	3.983813	0.040956	3.68232
Within Groups	41.19762	15	2.746508			
Total	63.08077	17				

Single factor for soil moisture in 2004 fall

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	192.2375	2	96.11873	19.97489	5.9E-05	3.68232
Within Groups	72.17967	15	4.811978			
Total	264.4171	17				

ANOVA results for Table 3.5

Two factor for ASP

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
LFS	487.739	2	243.8695	8.977878	0.000524	3.204317
Year	1093.286	2	546.6429	20.12426	5.71E-07	3.204317
Interaction	124.1003	4	31.02508	1.142166	0.348974	2.578739
Within	1222.352	45	27.16338			
Total	2927.477	53				

Single factor: ASP within 2003 bma

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	118.9078	2	59.45389	14.1284	0.000355	3.68232
Within Groups	63.12167	15	4.208111			
Total	182.0294	17				

Single factor: ASP within 2003 ama

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	247.1437	2	123.5719	3.034836	0.078208	3.68232
Within Groups	610.767	15	40.7178			
Total	857.9108	17				

Single factor: ASP within 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	245.7878	2	122.8939	3.361042	0.062219	3.68232
Within Groups	548.4633	15	36.56422			
Total	794.2511	17				

Single factor: ASP within Footslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	244.4509	2	122.2254	10.02163	0.001722	3.68232
Within Groups	182.9425	15	12.19617			
Total	427.3934	17				

Single factor: ASP within Backslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	290.7275	2	145.3638	8.608662	0.003236	3.68232
Within Groups	253.2863	15	16.88576			
Total	544.0138	17				

Single factor: ASP within Shoulder

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	682.2077	2	341.1039	6.508595	0.009226	3.68232
Within Groups	786.1232	15	52.40821			
Total	1468.331	17				

ANOVA results for Table 3.6

Two factor for NO_3^-

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
LFS	11335.72	2	5667.858	13.2625	2.96E-05	3.204317
Year	8581.926	2	4290.963	10.04064	0.000248	3.204317
Interaction	5146.158	4	1286.539	3.010437	0.027708	2.578739
Within	19231.18	45	427.3596			
Total	44294.98	53				

Single factor: NO_3^- within 2003 bma

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3246.889	2	1623.445	2.260392	0.138661	3.68232
Within Groups	10773.21	15	718.2137			
Total	14020.1	17				

Single factor: NO_3^- within 2003 ama

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	189.3823	2	94.69113	0.271693	0.765759	3.68232
Within Groups	5227.841	15	348.5227			
Total	5417.223	17				

Single factor: NO_3^- within 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13045.6	2	6522.801	30.29036	5.4E-06	3.68232
Within Groups	3230.137	15	215.3424			
Total	16275.74	17				

Single factor: NO_3^- within Footslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2260.999	2	1130.499	1.678621	0.219851	3.68232
Within Groups	10102.04	15	673.4693			
Total	12363.04	17				

Single factor: NO_3^- within Backslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3845.191	2	1922.595	3.553612	0.054535	3.68232
Within Groups	8115.386	15	541.0258			
Total	11960.58	17				

Single factor: NO_3^- within Shoulder

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7621.894	2	3810.947	56.38841	1.05E-07	3.68232
Within Groups	1013.758	15	67.58386			
Total	8635.652	17				

ANOVA results for Table 3.7

Two factor for NH_4^+

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
LFS	13796.41	2	6898.204	1.356297	0.267941	3.204317
Year	518974.6	2	259487.3	51.01935	2.69E-12	3.204317
Interaction	26380.21	4	6595.054	1.296693	0.285668	2.578739
Within	228872.6	45	5086.057			
Total	788023.8	53				

Single factor: NH_4^+ within 2003 bma

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.48339	2	5.741694	15.00349	0.000264	3.68232
Within Groups	5.74036	15	0.382691			
Total	17.22375	17				

Single factor: NH_4^+ within 2003 ama

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	40101.96	2	20050.98	1.31444	0.297851	3.68232
Within Groups	228816	15	15254.4			
Total	268917.9	17				

Single factor: NH_4^+ within 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	63.17444	2	31.58722	9.313186	0.002347	3.68232
Within Groups	50.875	15	3.391667			
Total	114.0494	17				

Single factor: NH_4^+ within Footslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	230686.6	2	115343.3	22.09517	3.38E-05	3.68232
Within Groups	78304.41	15	5220.294			
Total	308991	17				

Single factor: NH_4^+ within Backslope

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	80293.76	2	40146.88	22.64596	2.94E-05	3.68232
Within Groups	26592.08	15	1772.806			
Total	106885.8	17				

Single factor: NH_4^+ within Shoulder

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	234374.5	2	117187.2	14.17861	0.000349	3.68232
Within Groups	123976.1	15	8265.071			
Total	358350.5	17				

ANOVA results for Table 4.3

Single factor: snow depth at peak in 2004

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2532.194	2	1266.097	32.6197	3.45E-06	3.68232
Within Groups	582.2083	15	38.81389			
Total	3114.403	17				

Single factor: snow depth at peak in 2005

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2003.083	2	1001.542	15.42547	0.000229	3.68232
Within Groups	973.9167	15	64.92778			
Total	2977	17				

ANOVA results for Table 4.4

Single factor: pre-melt snow density in 2005

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3680.472	2	1840.236	0.930696	0.438113	4.737414
Within Groups	13840.88	7	1977.268			
Total	17521.35	9				

ANOVA results for Table 4.5

Single factor: pre-melt SWE in 2005

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5681.705	2	2840.852	47.1587	8.67E-05	4.737414
Within Groups	421.6818	7	60.24026			
Total	6103.387	9				

ANOVA results for Table 5.5

Single factor: TP in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.078783	2	2.539391	2.648837	0.103476	3.68232
Within Groups	14.38023	15	0.958682			
Total	19.45901	17				

Single factor: FW TP in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.53608	2	4.26804	2.476324	0.117674	3.68232
Within Groups	25.85308	15	1.723538			
Total	34.38916	17				

Single factor: TP Load in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	180.7442	2	90.37211	0.287725	0.754015	3.68232
Within Groups	4711.379	15	314.0919			
Total	4892.123	17				

Single factor: NO_3-N in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.070553	2	3.035276	1.516645	0.251259	3.68232
Within Groups	30.01964	15	2.00131			
Total	36.0902	17				

Single factor: FW NO_3-N in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.20771	2	5.603855	4.605102	0.027586	3.68232
Within Groups	18.25319	15	1.21688			
Total	29.4609	17				

Single factor: NO_3-N Load in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2411.06	2	1205.53	0.39803	0.678529	3.68232
Within Groups	45431.14	15	3028.743			
Total	47842.2	17				

Single factor: Sediment in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	32639.41	2	16319.71	0.999126	0.391429	3.68232
Within Groups	245009.8	15	16333.99			
Total	277649.2	17				

Single factor: FW Sediment in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5694.603	2	2847.301	0.21318	0.810417	3.68232
Within Groups	200344.8	15	13356.32			
Total	206039.4	17				

Single factor: Sediment Load in 2004

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1372987	2	686493.3	0.809621	0.463554	3.68232
Within Groups	12718783	15	847918.8			
Total	14091769	17				

APPENDIX II

Site Pictures

Picture 1 Watershed in late fall 2004.

Picture 2 Watershed in 2005 winter (*photo was taken in early February*).

Picture 3 Runoff plots (covered with snow) and runoff collection bags.

Picture 4 Central depression at the end of snowmelt runoff period in 2005.